Project/Process Simulation Modeling using Discrete Event Construction Simulation Language Stroboscope

by

Noman Zaheer

A Thesis Presented to the

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In Partial Fulfillment of the
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In

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To My Parents

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Praise and thanks to **Almighty Allah**, the most Gracious, the most Merciful with whose gracious help it was possible to accomplish this task, and peace and Blessings of **Almighty Allah** be upon his **Prophet Mohammed** (SAW).

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THESIS ABSTRACT

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Title of Study : Project/Process Simulation Modeling Using Discrete Event Construction Simulation Language STROBOSCOPE

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Construction processes are different from those encountered in other disciplines. They tend to be complex dynamic processes that require the collaboration of many distinct resources to perform activity-oriented task. Computer simulation of construction operations has been an active area of research for the past three decades. Although not fully adopted as an analysis tool in the construction industry, it has been widely accepted in the research community. STROBOSCOPE simulation system was selected as it could meet almost all requirements for developing complex models of any construction process. Since this is a relatively newly developed construction simulation language, very little recognition exists about the system, its capabilities, and its usage.

The objective of this research is to develop several simulation models concerning different domains of the construction field by using the simulation system: STROBOSCOPE. This work comprises three parts. Specifically these are; Simulation of Schedules of Linear Projects, Simulation of Stringing of Overhead Transmission Line Conductors and Overhead Ground wires, and Simulation of Time-Cost Trade-off for the Construction of Flow Line Pipes. The study will have significant effects on the construction industry both short-term and long-term. It presents the simulation system for construction industry use. This will also build confidence towards simulation usage for planning and decision-making purposes in construction industry. This thesis provides general recommendations for the selection of methods, equipment and manpower that have been found practical for different task being modeled.

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ملخص الرسالة

إسم الطالب : نعمان زهـــير

عنوان الدراسة : محاكاة عمليات التشييد بإستخدام لغة المحاكاة (ستروسكوب) .

الدرجة : ماجســـتير في العلوم .

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تختلف عمليات التشييد عن العمليات في التخصصات الأخرى . فهي تميل الى أن تكون عمليات معقدة وديناميكية ، تتطلب التوفيق بين الموارد في سبيل تنفيذ نشاطات معينة . وقد تم إستخدام المحاكاة على الكمبيوتـــر خلال الثلاثة عقود الماضية من خلال مشاريع بحثية وتطويرية لم تجد طريقها الى التطبيقات العملية في الشركات حتى الأن . تم تطوير نظام (الســـتروسكوب) في سبيل إستيفاء كافة متطلبات نمذجة عمليات التشييد على أرض الواقع . ولأنه جديد ، فإن قليل من المعلومات وكيفية الإستخدام معروفة عنه حتى الآن .

يهدف هذا البحث الى تطوير عدة نماذج للمحاكاة في صناعة التشييد ، بإستخدام لغة الأستروسكوب . ويتكون البحث من ثلاثة أجزاء . الجزء الأول يشمل نمذجة البرمجة الزمنية للمشاريع الطولية . الجزء الثاني يشمل نمذجة خطوط الكهرباء ، وأخيراً يشمل الجزء الثالث محاكاة للموازنة بين الوقت والتكلفة في المشاريع . وسيكون لهذه الدراسة تأثيـــرات في صناعة التشييد من الناحيتين قصيرة وطويلة المدى . حيث توضح أهمية إستخدام المحاكاة في التخطيط للمشاريع وإتخاذ القرارات الخاصة بها . كما يقدم البحث توصيات عامة لكيفية إختيار الطرق والمعدات والقوى العاملة من خلال النشـــاطات التي تمت محاكاتها ونمذجتها .

درجة الماجستير في العلوم
هندســـة وإدارة التشييد
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CHAPTER 1

INTRODUCTION

1.1 Background

Construction operations are work processes that are basic to the accomplishment of the physical components of a project. Typical examples are excavation, earthmoving and dewatering, formwork erection, concreting, and bricklaying. A construction operation can be characterized by its technology, its resources use, and its breakdown into work tasks and sequence. Therefore, concrete delivery process can be performed manually using wheelbarrows, mechanically with buggies, by crane and a bucket, by pumping, belt conveyors, chuting, or even by pressure spraying *(Halpin & Woodhead 1976)*.

Construction processes range from the very simple to very complex. In the design of construction operations, it is often necessary to make decisions regarding complex processes. These decisions include determining crew sizes, selecting equipment, establishing operating logic, or selecting construction methods. Associated with each decision are a series of outcomes such as construction cost and time. Decisions are made based on their expected outcomes. Several techniques are available to assess the outcomes associated with a particular method of performing a process. Experimenting with the real system, on one extreme, is very realistic but is expensive, slow, lacks generality, and sometimes impossible to do. Mathematical modeling, on the other

extreme, is very precise but requires that important aspects of the process be disregarded, requires a high degree of mathematical ability, and becomes too complex for most real construction situations. Simulation is a third technique. It is very convenient because, while being realistic, it is also inexpensive, fast, and flexible.

A simulation is imitation of the operations of a real world process or system over time. Whether performed by hand or by computer, simulation involves the generation of an artificial history to draw interference concerning the operating characteristics of the real system. The behavior of a system as it evolves overtime is studied by developing a simulation model. This model usually takes the form of a set of assumption concerning the operation of the system. These assumptions are expressed in mathematical, logical and symbolic relationship among the entities, or objects of interest, in the system. Once developed and validated, a model can be used to investigate a variety of "what-if" questions about the real world system.

1.2 Statement of the Problem

Computer simulation of construction operations has been an active area of research for the past three decades. Although not fully adopted as an analysis tool in the construction industry, it has been widely accepted in the research community. A number of reasons can be cited as to why practitioners do not apply simulation in the real life *(Chehayeb and AbouRizk 1998, AbouRizk and Halpin 1990, Shi and AbouRizk 1997, McCahill and Bernold 1993)*. Some of the reluctance can be attributed to the lack of knowledge among

practitioners about existence of such systems, in addition to the lack of experience in using the existing systems. Construction simulation systems previously available could not model typical construction processes with the necessary level of detail, multiple resource requirements and dynamic complexity of construction processes.

Construction simulation is a fast developing area but the programs in use, for simulating the different construction processes, were either Command line operating system based (i.e. dos, Unix etc.) or Fourth Generation Languages (i.e. languages that are developed in high level languages as Fortran, C, Pascal, etc). That was difficult to use as well as does not provide the flexibility to model the construction process realistically. Moreover, proper training is required to learn those languages. Additionally, these tools do not provide the graphical representation of the process/system under simulation. Other tools are specific purpose simulators that fit in one or few areas and do not give the flexibility of a programming language. Some tools are available that are window based and provide GUI for ease of use and better understanding of the system, but these tools lack the sophistication and flexibility needed for modeling real world construction processes. With the development of discrete-event construction simulation language, STROBOSCOPE, this void has successfully been filled. In addition to raw source code based simulation engine, STROBOSCOPE provides IDE as well as GUI for common users. Power user can feel comfortable with the flexibility and features set available under this simulation system with the capability to extend it through compiled DLLs under 32-bit windows operating system.

Since this is a relatively newly developed construction simulation language, so, very little recognition exists about the system, its capabilities, and its usage. There is a need of presenting the system with its application for various construction processes in order to enhance the industry awareness towards use of simulation, as major hurdles for simulation usage are resolved by the existence of STROBOSCOPE. In addition to modeling of processes with enhancements made available by STROBOSCOPE , those domains need to be explored which were thought to be infeasible from previous simulation tools' perspective.

1.3 Objectives

In order to overcome the previously described problems in application of simulation on a wider scale in construction industry, some relevant work needs to be done. This scales up to more important areas of construction industry; which can corroborate confidence building towards simulation usage for planning, forecasting and decision making purposes. In the accomplishment of these objectives, this research is to develop several simulation models concerning different domains of construction field by using the simulation system STROBOSCOPE.

The following tasks are selected for developing models.

1) Simulation of Schedules of Linear Projects
2) Simulation of Stringing of overhead transmission line conductors and overhead ground wires

3) Simulation of Time-CostTradeoff for the Construction of FlowLine pipes

In terms of developing models, the additional objectives are:

- Considering the diversity of resources and their specific characteristics
- Usage of resource selection schemes that resembles the way resources are selected for tasks in actual construction operations
- Modeling probabilistic material utilization, consumption and production
- Simulating models in various ways with sufficient replications to provide a basis for trends analysis purpose

1.4 Rationale / Significance

The study will have significant effects on construction industry both short- term and long-term. It will present the simulation system for construction industry use. The work will apply the STROBOSCOPE in areas which are of significant importance as either they were not previously modeled or previous models were not sufficiently realistic mainly due to the limited capabilities of other tools available at that time. Moreover, it will simulate those aspects of operations that were previously deemed infeasible due to the complexity, e.g., resource utilization on probabilistic or priorities basis. This will also be confidence building towards simulation usage for planning and decision making purposes in construction industry. Furthermore, it provides a better understanding of construction operations, their probabilistic nature, resource utilization, planning and

decision making. In addition, its gives opportunity to solve "what-if questions", relating the construction process under consideration.

1.5 Scope of the Work / Limitations

The work aims at presenting the simulation system for the use in construction industry, and to conduct simulation studies with different scenarios to provide a better understanding and more reliable estimation of the work being planed. It will provide general recommendations for the selection of methods, equipment and manpower that have been found practical for different task being modeled.

Simulation of Schedules of Linear Projects is the first part of wok. It will furnish suggestions for the use of simulation in scheduling of linear projects. It also provides comparison with widely used PERT method in regard of linear projects. Pert distribution will be used for the activity duration, which was found most prevalent through literature review. Moreover, the study is bound with the duration aspect of the project, and cost factor is not under the scope of study.

Simulation of Stringing of overhead transmission line conductors and overhead ground wires is the second part of the work. It task aims at conducting a simulation study with different scenarios of the stringing of overhead transmission line conductors and overhead ground wires in order to recommend the best combination for use in future projects. This project will provide general recommendations for the selection of methods,

equipment and manpower that have been found practical for the stringing of overhead transmission line conductors and overhead ground wires. This study confine to the prevalent practices in construction industry hence analyzes the different aspects of the method, adapted for modeling. The scope of this work remains to estimate the time required to construct a certain length of overhead power line and to know the cost associated with that certain length.

Simulation of Time-Cost Tradeoff for the Construction of Flow Line pipes is third part of the work. The study is essentially an attempt to use project level simulation as planning tool for flow line piping construction. It deals with cost and duration concerns of a project. Hence, the resources allocation is taken care of in terms of overall cost of that activity. Additionally it employees CPM network for sequencing of the activities and project planning, and stroboscope as simulation engine for that CPM network. If the project sequencing requires project's network definition technique other than CPM, then the methodology employed in this work might not be valid in its current form. Additionally, as CPM add-on for stroboscope is not capable of defining STS, STF, or FTF relation between activities, network of the project under consideration needs to be modified to define these relationships. One possible method, used in the study, is to use dummy activities for that purpose.

CHAPTER 2

LITERATURE REVIEW

Simulation is trying to duplicate the feature, appearance, and characteristics of the real system. The idea behind the simulation is to imitate a real-world situation mathematically, and then to study its properties and operating characteristics, and finally draw conclusions and make decisions based on the results of simulation *(Moore et. al, 1993)*.

A simulation is the imitation of the operation of a real world process or system over time *(Wadsworth 1998)*. Whether performed by hand or by computer, simulation involves the generation of an artificial history to draw interference concerning the operating characteristics of the real system. The behavior of a system as it evolves overtime is studied by developing a simulation model. This model usually takes the form of a set of assumption concerning the operation of the system. These assumptions are expressed in mathematical, logical and symbolic relationship among the entities, or objects of interest, in the system. Once developed and validated, a model can be used to investigate a wide variety of "what-if" questions about the real world system.

The usual steps of the simulation are *(Moore et. al, 1993)*

1. Define a problem
2. Introduce the variable associated with the problem
3. Construct a numerical model

4. Setup possible courses of action for testing
5. Run the experiment
6. Consider the results
7. Decide what courses of action to take

Alternatively, to build a model in a thorough and sound simulation study, following set of step can be followed. *(Wadsworth 1998)*

1. Problem Formulation
2. Setting of objectives and overall project plan
3. Model conceptualization
4. Data collection
5. Model translation
6. Verification
7. Validation
8. Experimental design
9. Production runs and analysis
10. Additional runs
11. Documentation and reporting
12. Implementation

Figure 2.1 presents the typical steps in a flow chart format, for better understanding of the process. Depending on the operation being modeled, further steps can be added, deleted, or modified.

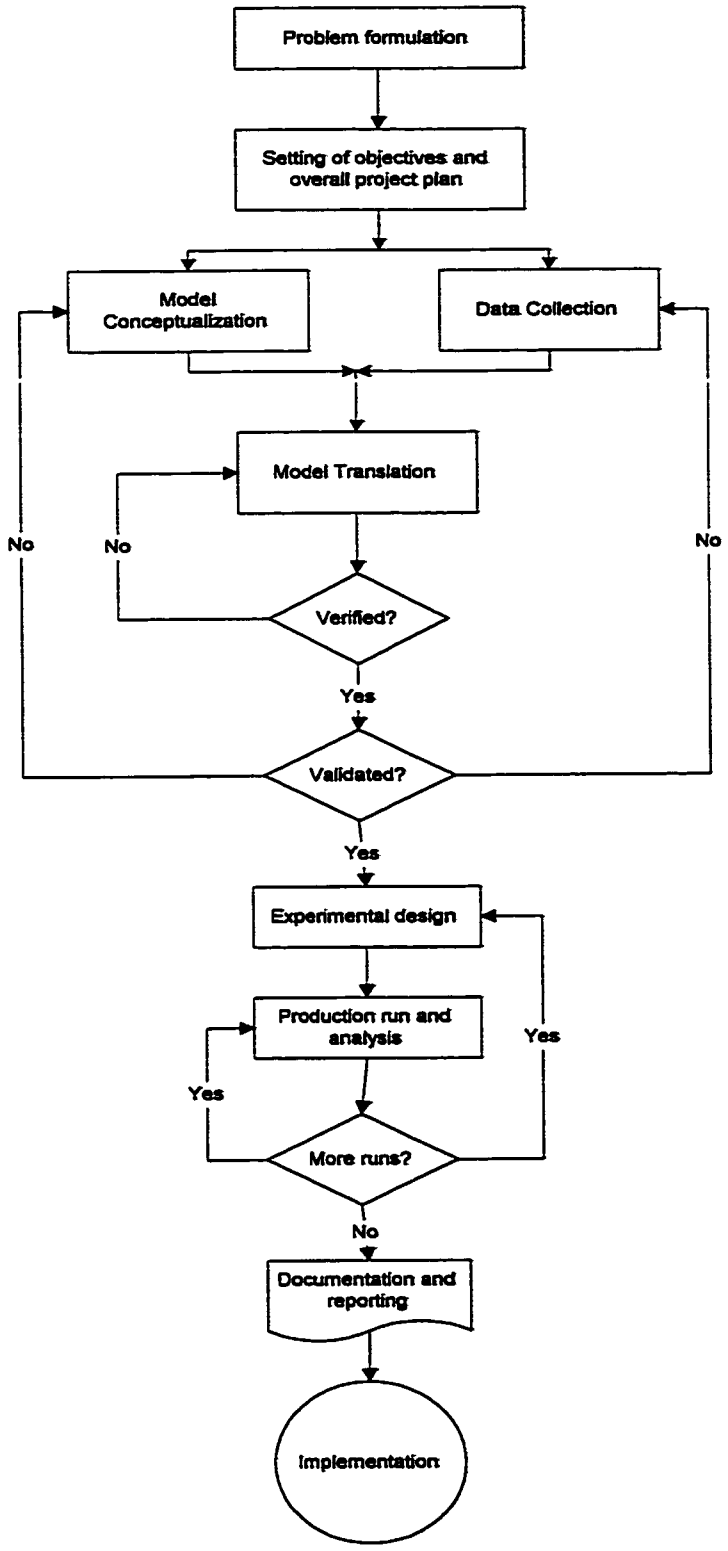

Figure 2.1: Typical Steps in a Simulation Study

2.1 History of Simulation

The history of simulation goes back 5000 years to Chinese war games (called weich'I) and continued through 1780, when Prussians used the games to help train their army. Since then, all major military power used war games to test out military strategies under simulated environments.

From military operational gaming, a new concept, Monte Carlo simulation, was developed a quantitative technique by the great mathematician Von Neumann during World War II. Working with neutrons at the Los Alamos Scientific Laboratory, Von Neumann used simulation to solved physics problems that were too complex or expensive to analyze by hands or by physical model. The random nature of neutrons suggested the use of roulette wheel in dealing with probabilities. Because of the gaming nature, Von Neumann called it the Monte Carlo model of studying law of chances. With the advent and common use of business computers in 1950's, simulation grew as a management tool, specialized computer languages were developed in 1960's (GPSS and SIMSCRIPT) to handle large-scale problems. *(Moore et. al, 1993)*

2.2 Main Advantages and Disadvantages *(Moore et. al, 1993)*

Every method has its advantages and disadvantages beside its limitations. For this reasons no method is considered perfect for all situations. In a similar way, Simulation as its advantages and disadvantages. Following is a brief overview of these cons and pros

2.2.1 Advantages *(Wadsworth 1998)*

1. It is relatively straight forward and flexible
2. Can be used to analyze large and complex real world problems that can't be solved by conventional quantitative analysis models
3. Sometimes it is the only method available
4. A simulation study can help in understanding how the system operates
5. New policies, operating procedures, decision rules, information flows, and organizational procedures can be explored without disrupting the ongoing operations of real system.
6. Hypothesis about how or why certain phenomena occur can be tested for feasibility
7. Time can be compressed or expanded allowing for a speed-up or slow-down of the phenomena under investigation
8. Insight can be obtained about the interaction of variables
9. Insight can be obtained about the importance of variables on performance of the system
10. Bottleneck analysis can be performed indicating where work-in-process, information, and materials are being excessively delayed
11. "What-if" questions can be answered. This is particularly important in designing of new systems
12. Simulation data are usually much less costly to obtain than the analogous data from the real system

2.2.2 Disadvantages *(Wadsworth 1998)*

1. Model building requires special training. Furthermore, if models are constructed by two competent individuals, the models may have similarities, but it is highly unlikely that they will be same
2. Simulation results may be difficult to interpret.
3. Simulation modeling and analysis can be time consuming and expensive
4. Simulation is used in some cases when an analytical solution is possible, or even preferable

2.3 Construction Operations

Construction operations contain the basic work processes in construction. At the same time, they are fundamental to the performance of support services in construction sites. Example ranges from simple processes such as laying of masonry concrete block to complex processes such as the horizontal earth boring.

A process can be divided into more basic work tasks. For example there are four work tasks in a typical excavation process: (1) a shovel excavates and loads dirt to a hauler, (2) the loaded hauler hauls away dirt, (3) the hauler dumps dirt at the designated site and (4) the unloaded hauler returns to the excavation site.

The full description of construction process requires (1) the identification of the construction technologies involved; (2) the identification and sequencing of the various work tasks that make up the various processes, and (3) the identification and allocation of the required resources for each work task

Construction operations (processes) may be grouped into different classifications, depending on which features are selected for classification various rationales have been suggested by finished product or structure (e.g., pile driving operations); by material (e.g., rock drilling operations); or by function (e.g., crane operations).

All construction operations require labor and machine resources in different proportions to achieve a productive activity that contributes to the completion of the project. Usually several methods and technologies are available to describe how these resources shall be allocated, and each construction operation is subject to constraints that influences the selection of the proper technology or method Therefore crew size and composition depend on the technological basis of the construction operation.

2.4 Construction Simulation

Construction operations are work processes that are basic to the accomplishment of the physical components of a project. Typical examples are excavation, earthmoving and de watering, formwork erection, concreting, and bricklaying. A construction operation can

be characterized by its technology, its resources use, and its breakdown into work tasks and sequence. Therefore, concrete delivery process can be performed manually using wheelbarrows, mechanically with buggies, by crane and a bucket, by pumping, belt conveyors, chuting, or even by pressure spraying *(Halpin & Woodhead 1976)*.

Construction operations contain the basic work process in construction. Their definition requires knowledge of the construction technology involved, a breakdown of processes into elemental work tasks, and the identification of resources. Practical descriptions for the performance of the construction operations must also indicate the conditions under which the processes and work tasks can be initiated, interrupted, or terminated. Planning and management of an efficient construction operation also requires information relating to the impact productivity and resource utilization. Any modeling methodology must be capable of meeting most (if not all) of the above requirement *(Halpin & Woodhead 1976)*. Therefore, the simulation for construction industry, although it based on similar concept and strategies, is quite different in nature from other industries or businesses. Construction projects are often associated with high degree of uncertainty stemming from the unpredictable nature of construction. The PERT method attempts to estimate the uncertainty in the project but not capable of fully meet the challenge. Simulation offers a tool that eliminates many of these limitations *(Ahuja et. al 1994)*.

The modeling capabilities of the CPM based planning tools (this include CPM, precedence diagramming, and PERT) do not allow modeling a dynamic

environment such as construction site. For this to occur a model capable of depicting the dynamic flow of resources and their interaction during the construction process must be used. Such tools already exist in the form of system simulation methods. Of these, CYCLONE *(Halpin and Riggs, 1992)* has received wide attention in construction research *(Ahuja et. al 1994)*.

2.4.1 Modeling Concepts

A model is a representation of a real world situation and usually provides a framework within which an investigation and analysis can be made of the given situation. Models contain data about a situation that, when interpreted according to certain rules or conventions, provide information about the situation relevant to pertinent decision processes. Models can be physical or conceptual A physical model is a mock-up or scale model of the prototype while a conceptual model is an abstraction of reality and is not intuitive to the uninstructed observer. Conceptual models are developed on a set of modeling and interpretive rules *(Halpin 1976)*.

Several techniques are available to assess the outcomes associated with particular method of performing a process. Physical modeling, on one extreme, is very realistic but is expensive, slow, lacks generality, and is sometimes impossible to perform. Mathematical modeling on the other extreme, is very precise but requires that important aspects of the process be disregarded, requires a high degree of mathematical ability, and becomes too complex for most real life construction situations. Simulation is the third

technique. It is very convenient because, while being realistic, it is inexpensive, fast, and flexible *(Martinez 1996)*.

2.4.2 Existing Modeling Systems

Simulation is a modeling process that imitates a real or imaginary dynamic system. Simulation involves the design of a model of the system and the performance of experiments on that model. The behavior or imaginary system can be predicted by observing the results of experiment the model. In the following paragraph, discrete event simulation will be discussed.

Dynamic systems or processes involved the passage of time. At any given point in time, the system is characterized by its state. In discrete event simulation, it is assumed that the state of a system changes instantaneously at specific times marked by events. Most construction processes can be effectively modeled using discrete-event simulation *(Martinez 1996)*.

2.4.2.1 General-purpose Programming Languages

Models created in general programming languages e.g. BASIC, FORTRAN, C / C++, can represent almost any real life process. They can be tailored to the very precise requirements of the model in question and can work very fast. Their use in construction has been demonstrated with models for equipment selection *(Teicholz 1963)*, for the

assessment of uncertainty in time and cost of underground construction *(Moavenzadeh and Markow 1976)*, for the estimation of project duration *(Carr 1979)*, and for the evaluation of resource allocation strategies *(Morua Padilla and Carr 1991)*.

Although some libraries are available to ease development of simulation models using general purpose programming languages, models created with them require that many components be built from scratch. This requires a tremendous amount of effort that is seldom justified Moreover, these models are geared towards a limited range of processes and are only useful for the particular model or class for which they are created.

2.4.2.2 Simulation-Specific Tools (Martinez 1996)

Many domain-specific and general purpose simulation tools exist. They can be classified as simulators or as simulation languages *(Law and Kelton 1991)*. Simulators are computer packages that allow the simulation of a specific class of systems with which little or no programming. Simulation languages are general in nature, but may have special features for certain types of applications. In general, simulation languages have the ability to model almost any kind of system.

Simulators and simulation languages can adopt one of several approaches, strategies, or decomposition methodologies. Three simulation strategies are commonly recognized: Event scheduling (ES), Activity Scanning (AS), and Process Interaction (PI). The strategy used by the simulation tool has a strong impact on the way a model is presented to the computer and on how the modeler views the world. For this reason, the

superiority of one strategy over the others has been the source of much discussion, and several comparisons have been made between them *(Hills 1973, Zeigler 1976)*. All strategies are considered equally general and powerful in terms of being or not being able to represent a particular problem. Particular strategies, however, lend themselves to model certain classes of models more easily.

ES is at the lowest level in terms of the support provided to the modeler and at the highest level terms of efficiency. An event-based simulation model is driven by the scheduling and execution of subroutines (events), that in turn schedule the execution of other subroutines. Since the ES strategy is very efficient, simulation tools often combine it with the PI or AS strategy.

A PI model is written from the point of view of the entities (transactions) that flow through a system. These entities undergo a process in which they attempt to acquire, take hold of, and release scarce resources. The PI strategy is very effective in the modeling of systems where the entities that move have many attributes that differentiate them and where the machines or resources that serve the entities have few attributes, a limited number of states, and do not interact too much. These systems are common in manufacturing and other industries that have been traditional users of simulation. For this reason, the PI strategy alone or combined with ES are the basis of most simulation tools and languages in use in the United States (e.g. GPSS, SLAM, SIMAN, Q-GERT, SIMSCRIPT).

In most construction process there is heavy interaction between machines, each of which can occupy several locations, have many attributes, and be in several states. This makes it very difficult to use PI tools in construction. Despite these difficulties, languages based on the PI strategy have been used for earth-moving operations *(Willenbrock 1972)* and repetitive housing unit construction *(Ashley 1980)*.

An AS model is written from the point of view of the various activities that can take place. The modeler focuses on identifying activities and the conditions under which the activities can happen. There is no distinction between flowing entities and machines; they are all resources. An AS tool constantly scans activities to see if they can take place. When an activity can take place, it is carried out.

Simulation languages based on the AS strategy, in contrast with PI, are very strong in modeling systems with highly interdependent components subject to complex activity startup conditions (i.e., many machines with distinct properties and states that must collaborate according to highly dynamic conditions). Since this is the very nature of construction operations, it is no surprise that construction academics and practitioners have used AS tools almost exclusively.

2.4.3 Review of Activity-Based Simulation Tools

Civil engineers and construction practitioners make heavy use of graphical sketches and drawings to visualize problems and specify details. Networks are a form of graphical

sketch capable of communicating complex concepts that would otherwise require explanations. In project level planning, for example, networks are very effectively used in the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT).

2.4.3.1 GSP - General Simulation Program

The General Simulation Program (GSP) *(Tocher 1963)* introduced the concept of three-phase activity scanning. GSP was regarded as a "machine-based" (the original name for AS) "automatic programmer". The main design objective of GSP was runtime efficiency. As a consequence, a program written in GSP resembles a cipher with many single letter identifiers and keywords.

Wheel-charts were the first AS simulation networks. This later became known as Activity Cycle Diagrams (ACDs). Wheel-charts were developed by *(Tocher 1963)* as an aid in identifying conditional activities (C-Activities in GSP) and bound activities (B-Activities in GSP). A wheel chart consists of a set of boxes linked by arcs that represent a sequence of activities for each machine. When the number of arcs entering a mode is one, activity is bound (the activity can be scheduled to start as soon as the predecessor finishes). When more than one arc enters a node is one, the activity is bound (activity can be scheduled to start as soon as the predecessor finishes). When more than one arc enters a node, the activity is conditional (a scan needs to be made to determine if all of its predecessors have finished).

When the sequence of activities in which a machine participates can change, wheel-charts include circles. When arc enters an activity from a circle, the activity is conditional regardless of the number of arcs that enter it. It is clear that GSP models while quite simple to understand as networks, become indecipherable when represented in machine-readable form. Its commands based model development represent the difficulty in use for common usage in addition to the its simulation weaknesses.

2.4.3.2 HOCUS - Hand Or Computer Universal Simulator

Hand Or Computer Universal Simulator (HOCUS) enhanced and popularized the concept of Activity Cycle Diagrams *(Hills 1973)*. A HOCUS ACD consists of Queues (circles) and Activities (boxes) connected by arrows. In contrast to a wheel-chart, the path followed by entities must alternate between Queues and Activities. The connection between the nodes has a pattern that indicates the type of entity that flows through it. Queues and Activities are identified by their numbers, which are placed towards the top-left on Activities.

A HOCUS model is conveyed to the computer through interactive input forms where the details of the nodes and the entities of the model are specified. The information specified inside the Activity usually describes it completely. With different Activities compete resources from the same Queues, HOCUS gives priority to the Activity with the lowest number. The entities in the system can have several integer-valued attributes identified with letters. The specification for Activities allows the manipulation of these attributes through two-letter options.

Although HOCUS is not well known in the United States, it is popular in Europe where it has been the subject of several books and has been used for numerous large-scale simulations in several industries *(Poole and Szymankiewicz 1977, McDonald, Turner and Szymankiewicz 1988)*. Although, it was the enhancement to GSP, it still represented most of the same weaknesses that was part of the GSP.

2.4.3.3 CYCLONE - Cyclic Operations Network

Cyclic operations Network (CYCLONE) was specifically designed for construction *(Halpin & Woodhead 1976)*. CYCLONE is purely network based (i.e., the network contains the complete model) and as a consequence is very simple. A CYCLONE network is an extended version of an ACD, Conditional activities are called Combis and are drawn with a slash on the top left corner of the box. Bound activities are called Normals, they are distinguished from conditional activities and are drawn as plain rectangles. Queues are drawn as circles but with a slash in the bottom right corner so as to resemble the letter Q. All the nodes in a CYCLONE network are identified by unique integer.

In CYCLONE, only the conditional Activities (Combis) need to be preceded exclusively by Queues. Combis start when none of the preceding Queues are empty. When several Combis contend for the resources in a Queue, priority is given to the Combi with lowest number. Bound Activities (Normals) can be preceded by any node but a Queue and start immediately after a predecessor finishes. The entities that flow through

a CYCLONE network are indistinguishable and interchangeable. They cannot have properties assigned to them. Special function nodes can multiply and consolidate entities as well as control the simulation run length

The small number of nodes and simple rules of CYCLONE make it very easy to use as both an analysis and communication tool Numerous construction processes have been modeled using CYCLONE. They include concrete batch plant operations *(Woods and Harris 1980, Lluch and Halpin 1982)*, and tunneling *(Touran 1987)*. There are at least four CYCLONE implementations:

Mainframe CYCLONE *(Halpin 1976)*

INSIGHT *(Kalk 1980)*

UM-CYCLONE *(Ioannou 1989)*

MicroCYCLONE *(Halpin 1990)*.

Unfortunately, the pure network characteristic of CYCLONE imposes limits that do not allow us to model processes at the level of detail required to make decisions. Three limitations are recognized to have the most impact:

- the inability to recognize differences between similar resources (i.e., the properties of resources)
- the inability to recognize the state of the simulated process

- the inability to make dynamic use of resource properties and the state of the simulation to define model behavior

Other than these limitations, CYCLONE was also a commands based program that is difficult for mainstream use.

2.4.3.4 RESQUE

RESQUE *(Chang 1986)* was designed as a significant enhancement to CYCLONE where the model is not limited to the information conveyed by the network. In addition to the CYCLONE network, a RESQUE model has an overlay that defines resource distinctions and increases simulation control. The overlay follows a Process Description Language (PDL) specific to RESQUE.

RESQUE sought to overcome the resource characterization capabilities missing in CYCLONE. The solution presented by RESQUE through PDL is a significant improvement over CYCLONE insofar as recognizing distinctions among resources that flow through the same path. RESQUE also had the same shortcoming as it does not provide any graphical user interface for model development instead depends on commands based on PDL.

2.4.3.5 COOPS

The COOPS construction simulation system (Liu 1991) is an extension to CYCLONE that was completely designed and implemented using an object oriented programming language. The simulation network is a collection of objects such as activities, queues, and links that are drawn interactively on the screen. These perform the simulation by reacting to messages sent from other objects. Moreover, "specific resources" are represented as separate objects to allow the collection of statistical information at the individual level. In addition, COOPS uses calendars to preempt activities during breaks and has the ability to generate and consolidate resources at links.

COOPS' interactive graphical model definition is a great improvement over previous construction simulation systems. Modeling elements are picked, placed and moved directly on the screen, and the need to enter a textual equivalent of the network is removed.

2.4.3.6 CIPROS

CIPROS (Odeh 1992) is both a process level and project level-planning tool. It contains an expandable knowledge base of construction techniques and methods; and makes ample use of a hierarchical object oriented representation for resources and their properties.

CIPROS extends its resource characterization capabilities beyond RESQUE by allowing multiple real properties for resources as well as more complex resource

selection schemes. It integrates process level and project level planning by representing activities through process networks, all of which can use a common resource pool. CIPROS does not provide access to the state of the simulation. This work has similar limitations in terms of usage and addressing of customer base as for COOPS.

2.4.4 Recent Advances in Construction Simulation

DISCO *(Huang et. al 1994)* is pre-processor and postprocessor to Micro-CYCLONE. The pre-processor is an interactive graphical user interface similar to COOPS'. The post-processor animates a simulation by "playing back" various statistics as they occurred during the simulation run.

AP3 *(Sawhney and AbouRizk 1995)* is a three-tiered planner that divides work into the project, operation, and process level. The process level component is based on CYCLONE. AP3 generates SLAM code.

2.4.5 Limitations Exhibited by All Other Construction Process Simulation Tools

The following issues are very common in construction operations and cannot be modeled, even with infinitely complex networks, by CYCLONE, RESQUE, COOPS or CIPROS. These issues can be modeled very easily by Stroboscope. *(Martinez 1996)*

- Uncertainty in the amount of resources consumed and produced. For example, the

amount of earth scraped by a scraper is uncertain and must be accounted for accurately as it moves through a network. The amount scraped must be hauled and eventually dumped. Other examples include the amount of rock fragments that result from a dynamite blast and the amount of muck that must be removed in the construction of a tunnel.

- Processes containing operations with non-stationary duration. For example, the hauling time in the construction of a road depends, among other factors, on haul distance. Since haul distance varies continuously, the parameters for the time distribution are a function of how much earth has been moved. Another example is an operation that is sensitive to the number of times it has been performed in the same process (learning curves).

- Processes that depend on properties of non-homogenous sets of similar resources. For example, the hauling time for a flatbed containing several different types of steel shapes depends on the weight of the flatbed and on weight of the steel shapes. In order to determine the gross weight, the weight of the steel shapes must be summed up. This cannot be done when only the attributes of the "set header" are accessible (RESQUE and CIPROS).

- Processes containing operations that are not activated unless complex resource requirements are met. (I.e., that depends on multiple properties of different types of resources in different locations). For example, loading a flatbed with steel shapes

only if any of the flatbeds available (characterized by length and payload) can be loaded with steel shapes (must bc shorter than the flatbed) to at least 80% of payload by any of the cranes available (the crane must be able to lift the steel shape).

The following capabilities, not available in either CYCLONE, RESQUE, COOPS, or CIPROS, are either required, or facilitate the solution of a wide variety of problems.

1. The ability to assign values to the properties of resources at simulation runtime.
2. The ability to work with, and produce, derived quantities such as cost.
3. The ability to collect statistics on any aspect of the simulated process.
4. The ability to access resource properties aggregated over several resources.
5. The ability to produce formatted output while the simulation is running for use in animation and graphing programs.
6. The ability to perform multiple replications according to a wide variety of methods.
7. The ability to implement variance reduction techniques such as common random numbers and antithetic variates.
8. The ability to call functions written in conventional programming languages such as C, C++, and FORTRAN.

2.5 STROBOSCOPE Simulation Language

In order to model a construction process realistically, a simulation tool must make dynamic use of the state of simulation and the properties of resources in numerous ways that cannot be foreseen at the time the simulation system was designed. In order to achieve this the simulation system must be programmable. This is the difference between a simulation language and a simulator. Previously existing simulation tools for construction are simulators and do not meet these requirements. STROBOSCOPE presents a radical departure from other construction systems. STROBOSCOPE is an acronym for State and ResOurce Based Simulation of Construction ProcEsses. It is a programming language specifically designed to model construction operations. STROBOSCOPE models are based on a network of interconnected modeling elements and on a series of programming statements that give the elements unique behavior and control the simulation. The STROBOSCOPE language is fully described in *(Martinez 1996)*.

SYMBOL	NAME	EXPLANATION
CutSheet	Queue	is a holding place (buffer) for 0, 1, or several resources waiting to become involved in the succeeding combination activity. Queues may contain generic or characterized resources. The latter are distinct from one another and they can be traced as individuals through various network nodes during simulation. The logic describing the ordering of resources upon entry into a queue of characterized resources is termed a DISCIPLINE.
Transport	Normal (activity)	Describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. May require a single resource or no resource at all.
Fabricate	Combi (-nation activity)	Like a normal, describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. Unlike a normal, requires several resources in combination for its performance and draws what is needed from the queue(s) that precede it.
AwaitTransport	Consolidator	Acts as a counter up to n (n is an integer value specified with the node): after n resources have been released into the consolidator, the consolidated set will be released from it.
WAT	Link	Shows flow logic. Should be labeled to meaningfully describe the resources that flow through it. If the link emanates from a queue, a DRAWORDER may be specified to sequence resources being drawn from the queue.
GoodBad	Fork	Describes a split in a resource's flow path. Incoming resources are routed along one path or another in a probabilistic or deterministic fashion, so the node is called a probabilistic fork or a decision node respectively. Each link emanating from it carries a likelihood or a statement evaluating to true/false for being followed by any specific resource arriving at the fork during simulation. The resource's actual path is determined at run time.
SpecialArea A	Assembler	Shows that 2 or more resources are being assembled into a single unit resource which is of the compound (a special kind of characterized) resource type.

Figure2.2: Some selected STROBOSCOPE symbols

The character of STROBOSCOPE arises from its ability to dynamically access the state of the simulation and the properties of the resources involved in an operation. The state of the simulation refers to such things as the number of trucks waiting to be loaded; the current simulation time; the number of times an activity has occurred; and the last time a particular activity started. Access to the properties of resources means that operations can be sensitive to properties- such as size, weight and cost- on an individual (the size of the specific loader used in an operation) or an aggregate basis (the sum of the weights of a set of steel shapes waiting to be erected).

STROBOSCOPE modeling elements have attributes—defined through programming statements—that define how they behave throughout a simulation. Attributes represent such things as the duration or priority of an activity, the discipline of a queue, and the amount of resource that flows from one element to another. Most attributes can be specified with expressions and have default values that provide the expected behavior. Expressions are composed of constants; system maintained variables that access the state of the simulation and the properties of resources; user-defined variables; logical, arithmetic, and conditional operators; and scientific, statistical, and mathematical functions. The attributes of STROBOSCOPE modeling elements allow simulation models to consider uncertainty in any aspect (not just time), such as the quantities of resources produced or consumed (e.g., the volume of rock resulting from a dynamite blast) *(Martinez 1996)*.

Attributes also allow models to dynamically select the routing of resources and the sequence of operations; to allocate resources to activities based on complex selection schemes; to combine resources and dynamically assign properties to the resulting compound resource; and to activate operations subject to complex startup conditions not directly related to resource availability (e.g., do not blast rock until all crews of all trades have left the vicinity, the wiring has been inspected, and there are less than 10 minutes left in the current shift).

STROBOSCOPE can be extended via add-ons written in a high-level compiled language such as FORTRAN or C++. STROBOSCOPE can also be controlled via OLE

Automation by other applications. A STROBOSCOPE add-on is a 32-bit MS Windows Dynamic Link Library that extends the STROBOSCOPE language with new statements, functions, and variables. The code within the add-on can call back into the simulation engine using STROBOSCOPE's Application Programming Interface (API) described in *(Martinez 1996)*.

Add-ons are loaded into STROBOSCOPE with the LOADADDON statement:

LOADADDON "C:\Program Files\Strobos\Add-Ons\AddOn.dll";

Once an add-on is loaded, its statements, functions and variables can be used as if they were a standard part of the language.

CHAPTER 3

METHODOLOGY

3.1 Selection of Tool

Construction processes are different from those encountered in other disciplines. They tend to be complex dynamic processes that require the collaboration of many distinct resources to perform activity-oriented task. The oldest and most widely used construction process simulation system is CYCLONE *(Halpin 1976)*. Over the years, many researchers have enhanced CYCLONE's capabilities in different ways. These enhancements include extensions that enable CYCLONE to handle learning curve; keep track of cost; and model transient effects. Other researchers have developed entirely new systems that build upon the basic CYCLONE concepts, notably RESQUE *(change 1986)*, COOPS *(Liu 1991)*, and CIPROS *(Odeh 1992)*. In addition, other systems have been developed for the modeling of construction at the project level.

In order to model construction processes realistically, a simulation tool must make dynamic use of the state of simulation and the properties of resources in ways that cannot be foreseen a the time simulation system was designed. In order to achieve this, the simulation system must be programmable. The tool selected to use for modeling purpose, have to be able to address this aspect. STROBOSCOPE simulation system was selected as it could meet almost all requirements for developing complex model of any

construction process. Previously existing simulation system tools for construction were mostly simulators and do not meet these requirements.

STROBOSCOPE represents a radical departure from other construction simulation systems. It is a programming language that represents resources as objects that have assignable, persistent, and dynamic properties. Also, it can actively and dynamically take into consideration the state of the simulated process. Another major difference between STROBOSCOPE and other tools is its open design. The input/output to a model are determined at two levels. The first level is using STROBOSCOPE's built-in programmability. The second level is by extending STROBOSCOPE through Dynamic Link Libraries (DLLs) created with high level complied languages such as C,C++, and FORTRAN. A more detailed comparison of STROBOSCOPE to several process and project simulation tools can be found in *(Martinez 1996)*.

3.2 Selection of Areas for Model Development

This research aims at developing simulation models concerning different domains of construction field by using the simulation system STROBOSCOPE. The selection of domains is dependent on many variables as

- Lack of previous research in that area
- Absence of STROBOSCOPE's utilization for that purpose
- Domain of works or projects of more significance

- Projects with more variations or with more cost/schedule overruns
- Or to get the advantage of more powerful simulation language and added features

On the above considerations, the following tasks are selected for developing simulation models in STROBOSCOPE.

1. Simulation of Schedules of Linear Projects
2. Simulation of Stringing of overhead transmission line conductors and overhead ground wires
3. Simulation of Time-Cost trade-off for the construction of flowlines pipes

3.3 Collection of Data required for Simulation Models

In development of simulation models, after problem formulation the first step is of model conceptualization and data collection. Data required for building a simulation model varies depending on task or project under consideration but as a starting point five "M" can cover almost all the data required. The first "M" and most essential is knowledge of Method or procedure being used for accomplishing a task. Here multiple methods for the same task can also be taken into consideration as to find out the most feasible method. Second "M" represents Materials. Most task requires several materials, combined with different types of these materials adds the complexity to any process and makes it difficult to find out the optimum combination of all. Third "M" defines Manpower requirement for that task, usually in crew's form. Fourth "M" stands for Machine or

equipment requirements. These include everything from hand tools to heavy machinery. Final "M" is for Minutes or in other words time requirement for completion. This, of course ,in most cases, is not a static quantity and depends of many variables like area, atmosphere/season of year, ground conditions, working conditions, labor rules etc. In order to cater these difficulties in estimation, suitable distribution can be used and the same approach will be followed wherever necessary.

3.4 Model Translation

Once data necessary for model development is at hands, Conceptual model can be translated in STROBOSCOPE using its graphical user interface (GUI) and/or integrated development environment (IDE). STROBOSCOPE models consist of a network of interconnected links and nodes and a series of programming statements that define the model's behavior and control the simulation. At an abstract level, network consists of Combis (rectangles with cut-offs in the top-left corner), Normals (rectangles), Queues (large circles with slash in the bottom right corner), and Forks (smaller circles with an inscribed triangle). The links connecting elements are defined through arrows. Resources move from node to node in the direction of arrows. A detailed discussion of the elements available for modeling and their usage can be found in *(Martinez 1996)*.

The network provides a high level representation of the operation. More specific details of the model are shown only in source listing. Network can be build using the GUI of STROBOSCOPE and the further details can be modeled at lower level using IDE of

STROBOSCOPE, or the model can entirely be model using IDE starting from the scratch. The choice of the platform depends on model being developed and its complexity as well as the user expertise with STROBOSCOPE and preferences.

3.5 Verification and Validation *(Law and Kelton 1991, Wadsworth 1998)*

There are two parts of testing procedure. *Verification,* which is determining that a simulation computer program performs as intended i.e. debugging the computer program. Thus, verification checks the translation of the conceptual simulation model into a correctly working program. Second part, *Validation,* is concerned with determining whether the conceptual simulation model is an accurate representation of the system under study.

Verification will be done by testing the developed models on an example project/process. In addition, trace run option of SROBOSCOPE provides a basis for verification of model. Trace run breaks and runs the model line-by-line, as well as provides the result for every line execution for interpretation.

There are several procedures for the Validation of the model but probably one of the most important is three-step approach to validation *(Law and Kelton 1991)*. The developed models can be validated by utilization of the procedure that consists of the following three steps.

1. **Develop a model with high face validity**

The primary objective during the first step is to develop a model with high face validity, i.e., a model that, on the surface, seems reasonable to people who are knowledgeable about the system. Following should be included to accomplish the task

- Conversation with system Experts
- Observation of the system
- Existing theory
- Relevant results from similar simulation models
- Experience / intuition

2. **Test the assumptions of the model empirically**

The goal of this step is to test quantitatively the assumptions made during model development. If a theoretical probability distribution has been fitted to some observed data and used as input to simulation model, the adequacy of fit can be assessed by the graphical plots. One of the most useful tool during this step is *Sensitivity Analysis*.

3. **Determine how representative the simulation output data are**

The most definitive test of a simulation model's validity is establishing that its output data closely resembles the output data that would be expected from actual (proposed) system. If a system similar to the proposed one exists, then a simulation model of the existing system is developed and it's output data are compared to those from the existing model itself. If the two sets of data compare favorably then the model of existing system is considered valid. The model is then modified so that it represents the proposed system.

3.6 Experimental Design

In Simulation, experimental design provides a way of deciding before the runs are made which particular configurations to simulate so that the desired information can be obtained with the least amount of simulating *(Law and Kelton 1991)*. Hence. the motivation for designing experiments is to obtain more (or better) information with less work.

Several different approaches or methods are available. In this study two approaches are followed, both utilizing pilot runs of the model. First, several runs are performed with different number of samples e.g. 5, 10, 20, etc. and confidence interval for *responses* are calculated for all runs. The sample size that provides confidence interval of response, covering other confidence intervals with bigger sample sizes gives the required sample size or number of runs.

Second approach utilizes the following formula for sample size calculation *(Mann 1995)*.

$$n = (z^2 . s^2) / E^2$$

where,

n = estimated sample size

z = value that corresponds to a prticular confidence level

E = maximum error of estimate for mean = z . s

s = sample standard deviation

In this approach, first a pilot run is performed with arbitrary sample. Then by using the standard deviation of this sample in above mentioned formula, the sample size is calculated. The conservative of both approaches is taken as required number of runs or sample size.

Reducing the variance of an output random variable of interest without disturbing its expectation, greater precision can be obtained e.g. smaller confidence intervals *(Law and Kelton 1991)*. Variance reduction techniques are used to reduce the number of replications required to achieve a given level of confidence in the results of a simulation model. Sometimes, as in the case of common Random Numbers, they are a requirement for the appropriate comparison of alternative system configurations *(Martinez 1996)*. STROBOSCOPE has several functions /commands for this purpose and provides means to accommodate several variance reduction techniques e.g. Common Random Numbers (CRN), Antithetic Variates (AV), etc. These techniques are used wherever applicable.

3.7 Simulation Runs and Output Gathering

Once the model has been defined, it is possible to perform automated experimentation that performs replications for various alternatives. The facilities include the ability to manipulate numerous statistics about the performance of a run and to establish confidence intervals on the derived quantities. STROBOSCOPE has built-in standard format report generation feature to gather and present output data of significance. In addition, it provides the several standard variables that can be used to gather data relevant

to many aspect of any variable. To extend it further, it has the capability to provide statistics based on user defined variables. This gives the basis to extract almost any kind of information from the simulation run provided that those statistics are being calculated at some point during the simulation run.

3.8 Analysis of Results

Simulation runs can provide loads of output data, and in many cases, that can be difficult to interpret. Due to the STROBOSCOPE's flexibility of output reports, it's much easier to get only the most relevant or required results from a simulation run. Results need to analyze for cost and/or duration purpose. Simulation run provides different aspects of these variables e.g. average, total, standard deviation, range, and criticality for any activity or for the whole project. Moreover, it provides time series data that shows the trend of variable under consideration and provides a basis for forecasting. Additionally, sensitivity analysis can be performed to observe the reactiveness of one variable to change in another variable or multiple variables. In case of sensitivity analysis, extensive output is needed to plot trends of variations, therefore, simulation model has to be aware of it and number of runs should be sufficient.

3.9 Conclusions

Final phase of any simulation is finding out some meaningful results and based on these results, decisions have to be made. Interpretation of results plays very important role in

decision making, therefore, simulation output and trends have to be read carefully and by someone with sufficient knowledge and expertise in the relevant area. Additional run option may be adopted at this stage if the need arises. Although, implementation of conclusions and decisions made based on results, is next step. The scope of this study remains limited to the presentation of results and recommendations.

CHAPTER 4

SIMULATION OF SCHEDULES OF LINEAR PROJECTS

4.1 Introduction

Linear repetitive projects, such as highways, high-rise buildings, pipelines and bridges, usually include the same set of construction activities that are repeated from one stage to another. Approaches for scheduling these kinds of projects can be classified into three categories *(Al-Harbi et al. 1996, Selinger 1980)*:

- Traditional network techniques such as the critical path method (CPM) *(O'Brien et al. 1985)*.
- Graphical approaches, such as the line of balance *(Carr and Meyer 1974; Arditi and Albulak 1986)*, the vertical production method *(O'Brien 1975)*, and the linear scheduling method *(Johnston 1981; Chrzanowski and Johnston 1986, Hanada 1986)*.
- Optimization approaches like the dynamic programming model *(Russell and Caselton 1988, Williams 1990)* and the linear programming model *(Reda 1990)*.

The critical path method (CPM) was developed during the late 1950's in two more-or-less parallel efforts. In one case, the US Navy and the Lockheed Company –the prime contractor– produced a technique they called "Project Evaluation and Review Technique" or PERT for short *(USA Navy 1958)*. This was a technique that produced a project schedule along with a statistical probability of meeting the schedule, and then evaluated and reviewed the progress of the project against this schedule *(The Associated General Contractors of America 1976)*.

In the other case, the E.I. du Pont de Nemours Company was constructing major chemical plants in America. These projects required that both time and cost be accurately estimated. The method of planning and control that was developed was originally called project planning and scheduling (PPS), and covered the design, construction, and maintenance work required for several large and complex jobs. PPS requires realistic estimates of cost and time and is thus a more definitive approach than PERT. It is this approach that has since been developed into the critical path method (CPM), which is finding increasing use in the construction industry. Although there are some uncertainties in any construction project, the cost and time required for each operation involved can be reasonably estimated and operations may then be reviewed by CPM in accordance with the anticipated conditions and hazards that may be encountered on the site. DuPont during the late 1950's was interested in scheduling refining renovation projects so that the time a refinery was not productive was minimized. A major consideration of their scheduling of course was the cost of project speedup. They wanted a schedule that was

optimally economical considering both the revenue losses caused by refinery inaction and the cost of project acceleration *(Antil and Woodhead 1990)*.

The objective of this research is to present how simulation could be used to improve the network schedule of linear projects and to check that PERT results are accurate up to which extent.

4.2 Need For Simulation

In spite of the widespread acceptance of CPM and PERT, schedule overruns continues to be a major problem. One possible reason is that network schedules calculated with CPM and PERT do not provide adequate information regarding the potential for schedule overruns. That is, CPM gives only a single number, which is intended to be the duration of a project. PERT is but slightly improvement in that it attempts to evaluate the probability of project duration by giving the expected completion time *(Halpin and Riggs 1992)*.

PERT consistently underestimates project duration, because it suffers of a condition known as "merge event bias". This condition occurs when several paths converge on a single node *(Figure 4.1)* and is caused by two reasons *(Halpin and Riggs 1992)*.

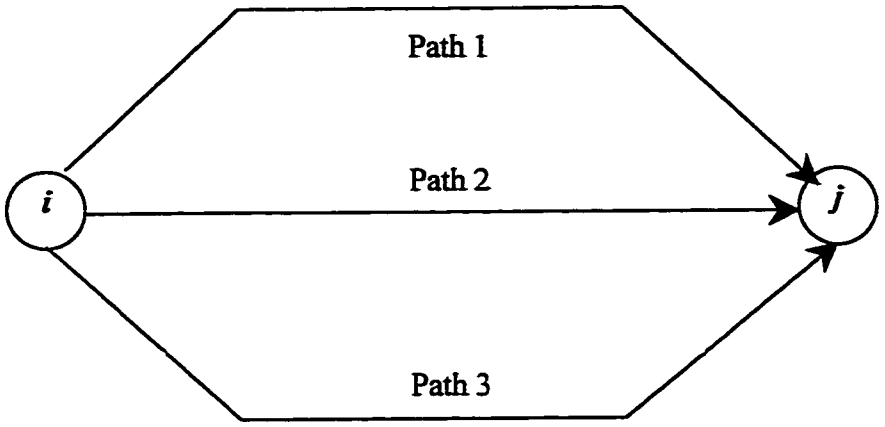

Figure 4.1: Merge event bias (Halpin and Riggs 1992)

First, PERT calculations give the early-expected finish time of this node as the summation of activity duration on the longest path leading to the node. This path then becomes part of the longest path through the network that determines expected project duration. Since the duration of the activities on the paths are random variables, it is possible that some other path converging on the node could have an activity with a random duration longer that its expected (mean) duration. Thus, the longer path would determine the early finish time of the node. That is, potential longer path is not taken into account in the PERT calculations leading to an underestimation of project duration. Additionally, the PERT method assumes statistical independence among them. This assumption allows the variance of activities along a path to be added, giving the variance of the duration of the project. The assumption of independence, however, may not always be appropriate. For instance, whether can create a positive correlation between activities, and delay in one activity may create a negative correlation between activities (Halpin and Riggs 1992). Simulation could solve the above difficulties. Because simulation of

schedule networks does not use a single number to represent activity duration, it avoids the merge event bias.

4.3 Example Project

An example project has been adopted *(Clough and Sears 1979; Reda 1990; Al-Harbi et.al. 1996)* that includes modifications that take into account having different duration for some activities in different stages. The example project is the relocation of 5 miles (8 Km) of natural gas pipeline. The project is divided into five stages: each stage represents one-mile (1.6 Km). Table 4.1 represents the project activities, their abbreviations, and probabilistic duration at different stages of the project. Figure 2 presents the CPM network for the first two stages of the example project.

Table 4.1: Duration Data for the Project Example

Activity Activity Abbreviation		Locate & Clear LC	Excavate EX	String pipe ST	Lay pipe LA	Test TE	Backfill BF
Stage 1 & 3	D(days)	1	4	2	5	2	1
Stage 4	D(days)	1	6	4	6	2	4
Stage 2 & 5	D(days)	1	3	3	6	2	1

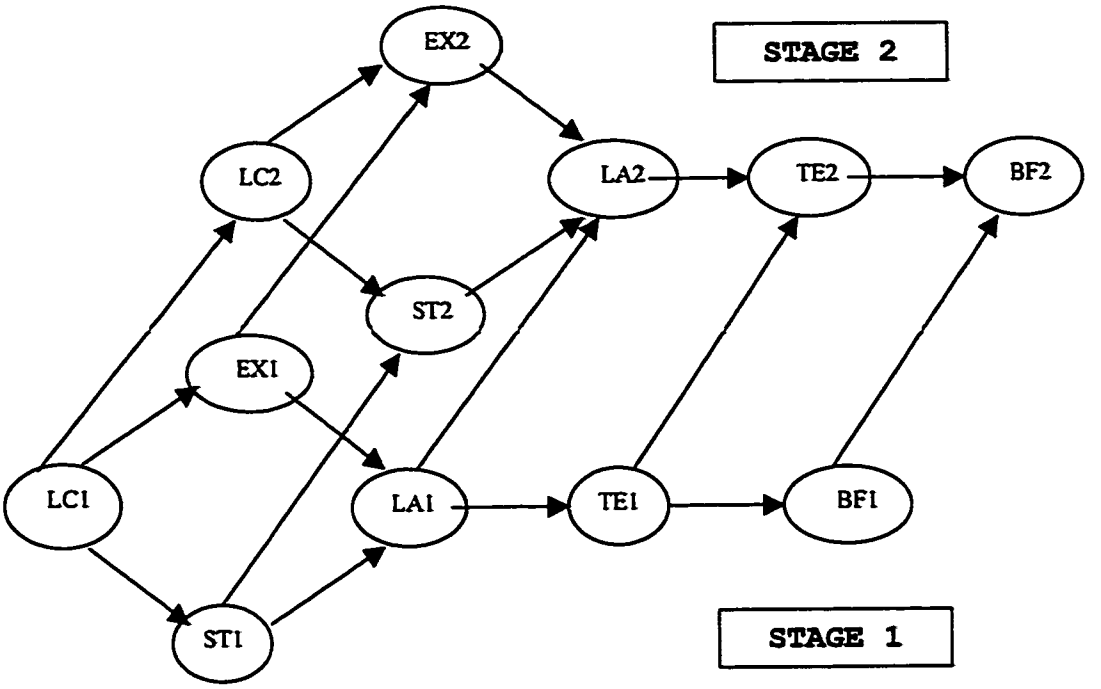

Figure 4.2: The Network Schedule of the first two stages of the example project

4.4 The Simulation Approach

CPM Add-on is used to model the network for simulation purpose in this case. The Probabilistic CPM Add-on for STROBOSCOPE is contained in file " CpmAddOn.dll ". This Add-on allows to define CPM networks with stochastic duration and to obtain various statistics about the project and its activities. The expressions for the duration of CPM activities can use the pre-defined variables provided by the add-on. The CPM network to be modeled does not have to have a single starting activity and single finishing

activity (a common CPM requirement). The CPM Add-on precedes every network with a dummy START and concludes it with a dummy FINISH.

Multiple cases have been considered and modeled using PERT and the STROBOSCOPE. This can give a better and representative view while considering the effectiveness of PERT that uses a simple approach. *Pert* and *Normal* distributions were used for these cases as the data available for input was well suited for Pert distribution and Normal distribution were used to see the difference while using for a specific case. Pert distribution used the form Pert[p0, mode, p100]. Here, p0 represents duration with zero percent probability or most optimistic value and p100 is duration with hundred percent probability or most pessimistic value. In the similar manner, Normal[mean, St.dev] was used with mean and standard deviation.

Each experiment consists of fifty 50-simulation runs, as came out through experimental design and the average total project duration was calculated. Each experiment was repeated ten times and average of all experiments for response i.e. total duration of project was calculated. Same procedure was repeated for all cases. Moreover, 95% confidence intervals were also established for all runs.

4.5 Results and Analysis

The output results for all cases are discussed individually, providing results and analysis for simulation runs ad using PERT method.

4.5.1 CASE 1: Project Example with Bell-Shaped Pert Distribution

This case used the bell-shaped pert distribution for calculating the duration of different activities. Table 4.2a shows the results for this case using PERT method. Table 4.2b presents the results for this case using STROBOSCOPE. Source code of STROBOSCOPE for Case 1 is presented in the Appendix A. The total project duration from PERT came out to be in side 95% confidence interval of average project duration from simulation. PERT's project duration was –0.21 σ from simulation average project duration.

TABLE 4.2a : PERT Calculation for Project Example with Bell-Shaped Pert Distribution

Activity	Predecessors	Probabilistic Duration	Expected Duration (a+4m+b)/6	ESD	EFD	Std Dev σ = (b-a)/6	Var σ²	Crit Path
LC1	—	Pert[0.5,1,1.5]	1	0	1	1/6	1/36	Y
EX1	LC1	Pert[1,4,7]	4	1	5	1	1	Y
ST1	LC1	Pert[1,2,3]	2	1	3	1/3	1/9	
LA1	EX1, ST1	Pert[1,5,9]	5	5	10	4/3	16/9	Y
TE1	LA1	Pert[1.5,2,2.5]	2	10	12	1/6	1/36	
BF1	TE1	Pert[0.5,1,1.5]	1	12	13	1/6	1/36	
LC2	LC1	Pert[0.5,1,1.5]	1	1	2	1/6	1/36	
EX2	EX1, LC2	Pert[1,3,5]	3	5	8	2/3	4/9	
ST2	ST1, LC2	Pert[1,3,5]	3	3	6	2/3	4/9	
LA2	LA1, EX2, ST2	Pert[2,6,10]	6	10	16	4/3	16/9	Y
TE2	TE1, LA2	Pert[1.5,2,2.5]	2	16	18	1/6	1/36	
BF2	BF1, TE2	Pert[0.5,1,1.5]	1	18	19	1/6	1/36	
LC3	LC2	Pert[0.5,1,1.5]	1	2	3	1/6	1/36	
EX3	EX2, LC3	Pert[1,4,7]	4	8	12	1	1	
ST3	ST2, LC3	Pert[1,2,3]	2	6	8	1/3	1/9	
LA3	LA2, EX3, ST3	Pert[1,5,9]	5	16	21	4/3	16/9	Y
TE3	TE2, LA3	Pert[1.5,2,2.5]	2	21	23	1/6	1/36	
BF3	BF2, TE3	Pert[0.5,1,1.5]	1	23	24	1/6	1/36	
LC4	LC3	Pert[0.5,1,1.5]	1	3	4	1/6	1/36	
EX4	EX3, LC4	Pert[2,6,10]	6	12	18	4/3	16/9	
ST4	ST3, LC4	Pert[2,4,6]	4	8	12	2/3	4/9	
LA4	LA3, EX4, ST4	Pert[2,6,10]	6	21	27	4/3	16/9	Y
TE4	TE3, LA4	Pert[1,2,3]	2	27	29	1/3	1/9	
BF4	BF3, TE4	Pert[2,4,6]	4	29	33	2/3	4/9	
LC5	LC4	Pert[0.5,1,1.5]	1	4	5	1/6	0	
EX5	EX4, LC5	Pert[1,3,5]	3	18	21	2/3	4/9	
ST5	ST4, LC5	Pert[,1,3,5]	3	12	15	2/3	4/9	
LA5	LA4, EX5, ST5	Pert[2,6,10]	6	27	33	4/3	16/9	Y
TE5	TE4, LA5	Pert[1.5,2,2.5]	2	33	35	1/6	1/36	Y
BF5	BF4, TE5	Pert[0.5,1,1.5]	1	35	36	1/6	1/36	Y

TABLE 4.2b : Example Simulation Results for Project Example with Bell-Shaped Pert Distribution and overall result for all runs

Number of replications performed : 50
Average Project Duration : 36.08
Std. Dev. of Project Duration : 3.15

CPM Activity	Time	ESD	LSD	EFD	LFD	FF	TF	%Critic
LC1	1.01	0.00	0.00	1.01	1.01	0.00	0.00	100.00%
EX1	3.99	1.01	1.01	5.00	5.00	0.00	0.01	97.80%
ST1	2.01	1.01	3.22	3.01	5.23	0.00	2.22	2.20%
LA1	5.00	5.00	5.29	10.01	10.30	-0.00	0.29	78.00%
TE1	2.00	10.01	23.23	12.01	25.23	0.00	13.23	0.00%
BF1	1.00	12.01	28.23	13.00	29.23	5.06	16.23	0.00%
LC2	1.00	1.01	5.39	2.00	6.39	-0.00	4.38	0.00%
EX2	2.99	5.00	6.66	7.99	9.65	-0.00	1.66	21.60%
ST2	3.01	3.01	7.29	6.02	10.29	-0.00	4.27	0.40%
LA2	6.00	10.06	10.30	16.07	16.30	0.00	0.23	84.40%
TE2	1.99	16.07	25.23	18.06	27.23	0.00	9.17	0.00%
BF2	1.00	18.06	29.23	19.06	30.23	3.93	11.17	0.00%
LC3	1.00	2.00	9.85	3.01	10.85	0.00	7.85	0.00%
EX3	4.00	7.99	10.85	11.98	14.85	0.00	2.87	15.60%
ST3	2.01	6.02	14.02	8.03	16.03	-0.00	8.00	0.00%
LA3	4.89	16.09	16.30	20.98	21.19	0.00	0.21	85.50%
TE3	2.01	20.98	27.23	22.99	29.24	0.00	6.25	0.00%
BF3	1.00	22.99	30.23	23.99	31.23	5.16	7.24	0.00%
LC4	1.00	3.01	14.10	4.01	15.10	0.00	11.10	0.00%
EX4	6.02	11.98	15.16	18.01	21.18	-0.00	3.18	14.50%
ST4	4.01	8.03	17.17	12.05	21.18	-0.00	9.13	0.00%
LA4	5.96	21.19	21.19	27.15	27.15	-0.00	0.00	99.80%
TE4	2.00	27.15	29.24	29.15	31.23	0.00	2.09	10.30%
BF4	3.96	29.15	31.23	33.11	35.19	2.09	2.09	10.30%
LC5	1.00	4.01	22.86	5.00	23.86	7.04	18.86	0.00%
EX5	2.99	18.01	24.22	21.00	27.21	6.15	6.21	0.20%
ST5	2.99	12.05	24.22	15.04	27.21	12.11	12.17	0.00%
LA5	5.99	27.15	27.21	33.14	33.20	-0.00	0.06	89.70%
TE5	1.99	33.14	33.20	35.13	35.19	0.06	0.06	89.70%
BF5	1.01	35.19	35.19	36.20	36.20	0.00	-0.00	100.00%

Average Project Duration = 36.089

Std. Dev. Of Project Duration = 2.994

95% C.I. on Project Duration = [35.238 , 36.941]

4.5.2 CASE 2: Project Example with Bell-Shaped Pert Distribution with Smaller Duration Ranges

This case used the same bell-shaped pert distribution but with smaller range of duration for all activities. Table 4.3a shows the results for this case using PERT method. Table 4.3b presents the results for this case using STROBOSCOPE. Source code of STROBOSCOPE for Case 2 is presented in the Appendix. The total project duration from PERT came out to be in side 95% confidence interval of average project duration from simulation. PERT's project duration was –0.25 σ from simulation average project duration.

TABLE 4.3a : PERT Calculation for Project Example with Bell-Shaped Pert Distribution with Smaller Duration Ranges

Activity	Predecessors	Probabilistic Duration	Expected Duration (weeks)	ESD	EFD	Stdev σ = (b-a)/6	Var σ²	Crit Path
LC1	—	Pert[1,2,3]	2	0	2	1/3	1/9	Y
EX1	LC1	Pert[4,5,6]	5	2	7	1/3	1/9	Y
ST1	LC1	Pert[2,3,4]	3	2	7	1/3	1/9	
LA1	EX1, ST1	Pert[5,6,7]	6	7	13	1/3	1/9	Y
TE1	LA1	Pert[2,3,4]	3	13	16	1/3	1/9	
BF1	TE1	Pert[1,2,3]	2	16	18	1/3	1/9	
LC2	LC1	Pert[1,2,3]	2	2	4	1/3	1/9	
EX2	EX1, LC2	Pert[3,4,5]	4	7	11	1/3	1/9	
ST2	ST1, LC2	Pert[3,4,5]	4	7	11	1/3	1/9	
LA2	LA1, EX2, ST2	Pert[6,7,8]	7	13	20	1/3	1/9	Y
TE2	TE1, LA2	Pert[2,3,4]	3	20	23	1/3	1/9	
BF2	BF1, TE2	Pert[1,2,3]	2	23	25	1/3	1/9	
LC3	LC2	Pert[1,2,3]	2	4	6	1/3	1/9	
EX3	EX2, LC3	Pert[4,5,6]	5	11	16	1/3	1/9	
ST3	ST2, LC3	Pert[2,3,4]	3	11	14	1/3	1/9	
LA3	LA2, EX3, ST3	Pert[5,6,7]	6	20	26	1/3	1/9	Y
TE3	TE2, LA3	Pert[2,3,4]	3	26	29	1/3	1/9	
BF3	BF2, TE3	Pert[1,2,3]	2	29	31	1/3	1/9	
LC4	LC3	Pert[1,2,3]	2	6	8	1/3	1/9	
EX4	EX3, LC4	Pert[6,7,8]	7	16	23	1/3	1/9	
ST4	ST3, LC4	Pert[4,5,6]	5	14	19	1/3	1/9	
LA4	LA3, EX4, ST4	Pert[6,7,8]	7	26	33	1/3	1/9	Y
TE4	TE3, LA4	Pert[2,3,4]	3	33	36	1/3	1/9	
BF4	BF3, TE4	Pert[4,5,6]	5	36	41	1/3	1/9	
LC5	LC4	Pert[1,2,3]	2	8	10	1/3	1/9	
EX5	EX4, LC5	Pert[3,4,5]	4	23	27	1/3	1/9	
ST5	ST4, LC5	Pert[,3,4,5]	4	19	23	1/3	1/9	
LA5	LA4, EX5, ST5	Pert[6,7,8]	7	33	40	1/3	1/9	Y
TE5	TE4, LA5	Pert[2,3,4]	3	40	43	1/3	1/9	Y
BF5	BF4, TE5	Pert[1,2,3]	2	43	45	1/3	1/9	Y

TABLE 4.3b : Example Simulation Results for Project Example with Bell-Shaped Pert Distribution with Smaller Duration Ranges and overall result for all runs

Number of replications performed : 50
Average Project Duration : 45.1
Std. Dev. of Project Duration : 1.09

CPM Activity	Time	ESD	LSD	EFD	LFD	FF	TF	%Critic
LC1	2.02	0.00	0.00	2.02	2.02	0.00	0.00	100.00%
EX1	5.00	2.02	2.02	7.01	7.01	0.00	0.00	100.00%
ST1	3.01	2.02	4.01	5.02	7.01	0.00	1.99	0.00%
LA1	6.00	7.01	7.01	13.01	13.01	0.00	0.00	100.00%
TE1	3.00	13.01	25.97	16.01	28.97	-0.00	12.96	0.00%
BF1	1.99	16.01	31.98	18.00	33.97	5.00	15.96	0.00%
LC2	1.99	2.02	6.82	4.01	8.81	-0.00	4.80	0.00%
EX2	3.99	7.01	9.00	11.01	13.00	0.00	1.99	0.00%
ST2	4.00	5.02	9.01	9.03	13.01	0.00	3.99	0.00%
LA2	7.00	13.01	13.01	20.01	20.01	0.00	0.00	100.00%
TE2	2.99	20.01	28.97	23.00	31.96	-0.00	8.96	0.00%
BF2	2.00	23.00	33.97	25.01	35.97	4.00	10.96	0.00%
LC3	2.00	4.01	11.98	6.01	13.98	0.00	7.97	0.00%
EX3	5.00	11.01	13.98	16.01	18.98	0.00	2.97	0.00%
ST3	3.01	9.03	17.00	12.04	20.01	-0.00	7.97	0.00%
LA3	5.97	20.01	20.01	25.99	25.99	0.00	0.00	100.00%
TE3	3.02	25.99	31.96	29.00	34.98	-0.00	5.98	0.00%
BF3	2.01	29.00	35.97	31.01	37.98	4.96	6.97	0.00%
LC4	2.00	6.01	16.98	8.01	18.98	0.00	10.97	0.00%
EX4	7.01	16.01	18.98	23.01	25.99	-0.00	2.97	0.00%
ST4	5.01	12.04	20.98	17.05	25.99	-0.00	8.94	0.00%
LA4	6.99	25.99	25.99	32.98	32.98	-0.00	-0.00	100.00%
TE4	3.00	32.98	34.98	35.97	37.98	-0.00	2.00	0.10%
BF4	4.98	35.97	37.98	40.95	42.96	2.00	2.00	0.10%
LC5	1.99	8.01	26.81	10.01	28.80	7.04	18.79	0.00%
EX5	4.00	23.01	28.98	27.01	32.98	5.97	5.97	0.00%
ST5	4.00	17.05	28.98	21.04	32.98	11.93	11.93	0.00%
LA5	7.00	32.98	32.98	39.97	39.97	0.00	0.00	99.90%
TE5	2.98	39.97	39.97	42.96	42.96	0.00	0.00	99.90%
BF5	2.01	42.96	42.96	44.97	44.97	0.00	-0.00	100.00%

Average Project Duration = 45.035

Std. Dev. Of Project Duration = 1.002

95% C.I. on Project Duration = [44.75 , 45.32]

4.5.3 CASE 3: Project Example with Bell-Shaped Normal Distribution with Smaller Duration Range

This case used the bell-shaped Normal distribution with same smaller range of duration for all activities as in case 2. Table 4.4a shows the results for this case using PERT method. Table 4.4b presents the results for this case using STROBOSCOPE. Source code of STROBOSCOPE for Case 3 is presented in the Appendix A. The total project duration from PERT came out to be in side 95% confidence interval of average project duration from simulation. PERT's project duration was –0.03 σ from simulation average project duration.

TABLE 4.4a : PERT Calculation for Project Example with Bell-Shaped Normal Distribution with Smaller Duration Range

Act Var	Predecessors	Probabilistic Duration	Expected Duration (rounded)	ESD	EFD	Sigma = (b-a)/6	Var σ^2	Crit Act
LC1	—	Normal[1,2,3]	2	0	2	1/3	1/9	Y
EX1	LC1	Normal [4,5,6]	5	2	7	1/3	1/9	Y
ST1	LC1	Normal [2,3,4]	3	2	7	1/3	1/9	
LA1	EX1, ST1	Normal [5,6,7]	6	7	13	1/3	1/9	Y
TE1	LA1	Normal [2,3,4]	3	13	16	1/3	1/9	
BF1	TE1	Normal [1,2,3]	2	16	18	1/3	1/9	
LC2	LC1	Normal [1,2,3]	2	2	4	1/3	1/9	
EX2	EX1, LC2	Normal [3,4,5]	4	7	11	1/3	1/9	
ST2	ST1, LC2	Normal [3,4,5]	4	7	11	1/3	1/9	
LA2	LA1, EX2, ST2	Normal [6,7,8]	7	13	20	1/3	1/9	Y
TE2	TE1, LA2	Normal [2,3,4]	3	20	23	1/3	1/9	
BF2	BF1, TE2	Normal [1,2,3]	2	23	25	1/3	1/9	
LC3	LC2	Normal [1,2,3]	2	4	6	1/3	1/9	
EX3	EX2, LC3	Normal [4,5,6]	5	11	16	1/3	1/9	
ST3	ST2, LC3	Normal [2,3,4]	3	11	14	1/3	1/9	
LA3	LA2, EX3, ST3	Normal [5,6,7]	6	20	26	1/3	1/9	Y
TE3	TE2, LA3	Normal [2,3,4]	3	26	29	1/3	1/9	
BF3	BF2, TE3	Normal [1,2,3]	2	29	31	1/3	1/9	
LC4	LC3	Normal [1,2,3]	2	6	8	1/3	1/9	
EX4	EX3, LC4	Normal [6,7,8]	7	16	23	1/3	1/9	
ST4	ST3, LC4	Normal [4,5,6]	5	14	19	1/3	1/9	
LA4	LA3, EX4, ST4	Normal [6,7,8]	7	26	33	1/3	1/9	Y
TE4	TE3, LA4	Normal [2,3,4]	3	33	36	1/3	1/9	
BF4	BF3, TE4	Normal [4,5,6]	5	36	41	1/3	1/9	
LC5	LC4	Normal [1,2,3]	2	8	10	1/3	1/9	
EX5	EX4, LC5	Normal [3,4,5]	4	23	27	1/3	1/9	
ST5	ST4, LC5	Normal [,3,4,5]	4	19	23	1/3	1/9	
LA5	LA4, EX5, ST5	Normal [6,7,8]	7	33	40	1/3	1/9	Y
TE5	TE4, LA5	Normal [2,3,4]	3	40	43	1/3	1/9	Y
BF5	BF4, TE5	Normal [1,2,3]	2	43	45	1/3	1/9	Y

TABLE 4.4b : Example Simulation Results for Project Example with Bell-Shaped Normal Distribution with Smaller Duration Ranges and overall result for all runs

Number of replications performed : 50
Average Project Duration : 44.9
Std. Dev. of Project Duration : 0.9

CPM Activity	Time	ESD	LSD	EFD	LFD	FF	TF	%Critic
LC1	2.00	0.00	0.00	2.00	2.00	0.00	0.00	100.00%
EX1	4.99	2.00	2.00	6.99	6.99	0.00	0.00	100.00%
ST1	3.02	2.00	3.98	5.02	6.99	0.00	1.98	0.00%
LA1	6.00	6.99	6.99	13.00	13.00	-0.00	0.00	100.00%
TE1	3.00	13.00	25.93	16.00	28.93	0.00	12.93	0.00%
BF1	2.03	16.00	31.94	18.02	33.96	4.97	15.94	0.00%
LC2	2.00	2.00	6.78	4.00	8.78	0.00	4.78	0.00%
EX2	4.03	6.99	8.95	11.02	12.98	-0.00	1.95	0.00%
ST2	3.99	5.02	9.00	9.01	13.00	-0.00	3.98	0.00%
LA2	6.99	13.00	13.00	19.99	19.99	0.00	0.00	100.00%
TE2	3.00	19.99	28.93	22.99	31.93	0.00	8.94	0.00%
BF2	1.99	22.99	33.96	24.98	35.95	4.00	10.97	0.00%
LC3	1.99	4.00	11.97	5.99	13.97	0.00	7.97	0.00%
EX3	5.00	11.02	13.97	16.02	18.96	0.00	2.94	0.00%
ST3	3.00	9.01	16.98	12.02	19.99	-0.00	7.97	0.00%
LA3	5.99	19.99	19.99	25.98	25.98	-0.00	-0.00	100.00%
TE3	3.00	25.98	31.93	28.98	34.93	-0.00	5.95	0.00%
BF3	1.99	28.98	35.95	30.97	37.94	5.01	6.97	0.00%
LC4	2.00	5.99	16.97	7.99	18.96	-0.00	10.97	0.00%
EX4	7.02	16.02	18.96	23.04	25.98	-0.00	2.94	0.00%
ST4	4.98	12.02	21.00	17.00	25.98	0.00	8.98	0.00%
LA4	6.99	25.98	25.98	32.97	32.97	0.00	-0.00	100.00%
TE4	3.00	32.97	34.93	35.98	37.94	0.00	1.96	0.30%
BF4	5.00	35.98	37.94	40.98	42.94	1.96	1.96	0.30%
LC5	2.01	7.99	26.78	10.00	28.79	7.00	18.78	0.00%
EX5	4.00	23.04	28.97	27.04	32.97	5.93	5.94	0.00%
ST5	4.01	17.00	28.96	21.01	32.97	11.96	11.96	0.00%
LA5	6.98	32.97	32.97	39.96	39.96	-0.00	0.00	99.70%
TE5	2.98	39.96	39.96	42.94	42.94	0.00	0.00	99.70%
BF5	1.99	42.94	42.94	44.93	44.93	0.00	-0.00	100.00%

Average Project Duration = 45.004

Std. Dev. Of Project Duration = 0.958

95% C.I. on Project Duration = [44.733 , 45.276]

4.5.4 CASE 4: Project Example with Skewed-to-Right Pert Distribution

This case used the skewed-to-right pert distribution for calculating the duration of different activities. Table 4.5a shows the results for this case using PERT method. Table 4.5b presents the results for this case using STROBOSCOPE. Source code of STROBOSCOPE for Case 4 is presented in the Appendix A. The total project duration from PERT came out to be in side 95% confidence interval of average project duration from simulation. PERT's project duration was –2.40 σ from simulation average project duration.

TABLE 4.5a : PERT Calculation for Project Example with Skewed-to-Right Pert Distribution

Activity	Predecessors	Probabilistic Duration	Expected Duration (rounded)	ESD	EFD	Stdev σ = (b-a)/6	Var σ²	Crit Path
LC1	—	Pert[1,1.5,4]	1.83	0	1.83	1/2	1/4	Y
EX1	LC1	Pert[1,3,8]	3.5	1.83	5.33	7/6	49/36	Y
ST1	LC1	Pert[1,2,5]	2.33	1.83	4.16	2/3	4/9	
LA1	EX1, ST1	Pert[1,4,10]	4.5	5.33	9.83	3/2	9/4	Y
TE1	LA1	Pert[2,2.5,5]	2.83	9.83	12.66	1/2	1/4	
BF1	TE1	Pert[1,1.5,4]	1.83	12.66	14.5	1/2	1/4	
LC2	LC1	Pert[1,1.5,4]	1.83	1.83	3.66	1/2	1/4	
EX2	EX1, LC2	Pert[,1,3,8]	3.5	5.33	8.83	7/6	49/36	
ST2	ST1, LC2	Pert[1,3,8]	3.5	4.16	7.66	7/6	49/36	
LA2	LA1, EX2, ST2	Pert[2,5,11]	5.5	9.83	15.33	3/2	9/4	Y
TE2	TE1, LA2	Pert[2,2.5,5]	2.83	15.33	18.16	1/2	1/4	
BF2	BF1, TE2	Pert[1,1.5,4]	1.83	18.16	20	1/2	1/4	
LC3	LC2	Pert[1,1.5,4]	1.83	3.66	5.5	1/2	1/4	
EX3	EX2, LC3	Pert[1,3,8]	3.5	8.83	12.33	7/6	49/36	
ST3	ST2, LC3	Pert[1,2,5]	2.33	7.66	10	2/3	4/9	
LA3	LA2, EX3, ST3	Pert[1,4,10]	4.5	15.33	19.83	3/2	9/4	Y
TE3	TE2, LA3	Pert[2,2.5,5]	2.83	19.83	22.66	1/2	1/4	
BF3	BF2, TE3	Pert[1,1.5,4]	1.83	22.66	24.5	1/2	1/4	
LC4	LC3	Pert[1,1.5,4]	1.83	5.5	7.33	1/2	1/4	
EX4	EX3, LC4	Pert[2,5,11]	5.5	12.33	17.83	3/2	9/4	
ST4	ST3, LC4	Pert[2,4,9]	4.5	10	14.5	7/6	49/36	
LA4	LA3, EX4, ST4	Pert[2,5,11]	5.5	19.83	25.33	3/2	9/4	Y
TE4	TE3, LA4	Pert[1,2,5]	2.33	25.33	27.66	2/3	4/9	
BF4	BF3, TE4	Pert[2,4,9]	4.5	27.66	32.16	7/6	49/36	
LC5	LC4	Pert[1,1.5,4]	1.83	7.33	9.16	1/2	1/4	
EX5	EX4, LC5	Pert[1,3,8]	3.5	17.83	21.33	7/6	49/36	
ST5	ST4, LC5	Pert[1,3,8]	3.5	14.5	18	7/6	49/36	
LA5	LA4, EX5, ST5	Pert[2,5,11]	5.5	25.33	30.83	3/2	9/4	Y
TE5	TE4, LA5	Pert[2,2.5,5]	2.83	30.83	33.66	1/2	1/4	Y
BF5	BF4, TE5	Pert[1,1.5,4]	1.83	33.66	35.5	1/2	1/4	Y

TABLE 4.5b : Example Simulation Results for Project Example with Skewed-to-Right Pert Distribution and overall result for all runs

Number of replications performed : 50
Average Project Duration : 36.53
Std. Dev. of Project Duration : 3.41

CPM Activity	Time	ESD	LSD	EFD	LFD	FF	TF	%Critic
LC1	1.82	0.00	0.00	1.82	1.82	0.00	0.00	100.00%
EX1	3.51	1.82	2.02	5.33	5.54	0.02	0.21	77.00%
ST1	2.33	1.82	3.53	4.14	5.86	0.12	1.71	17.70%
LA1	4.52	5.46	6.31	9.98	10.83	-0.00	0.85	51.60%
TE1	2.83	9.98	19.63	12.81	22.47	-0.00	9.66	0.00%
BF1	1.85	12.81	25.14	14.66	26.99	4.13	12.33	0.00%
LC2	1.83	1.82	4.25	3.64	6.07	-0.00	2.43	5.30%
EX2	3.49	5.37	6.62	8.86	10.12	0.01	1.25	37.60%
ST2	3.48	4.28	7.21	7.76	10.68	0.02	2.92	10.60%
LA2	5.48	10.45	10.83	15.93	16.31	0.00	0.38	76.50%
TE2	2.85	15.94	22.47	18.78	25.31	0.00	6.53	0.40%
BF2	1.83	18.79	26.99	20.62	28.82	2.91	8.20	0.00%
LC3	1.83	3.64	9.41	5.47	11.24	0.00	5.77	0.20%
EX3	3.51	8.87	11.46	12.38	14.97	0.00	2.59	20.90%
ST3	2.31	7.78	13.24	10.08	15.54	0.01	5.46	2.60%
LA3	4.65	15.98	16.31	20.63	20.96	0.04	0.33	77.80%
TE3	2.81	20.72	25.32	23.52	28.13	0.01	4.61	1.50%
BF3	1.81	23.53	28.82	25.34	30.63	3.51	5.29	0.60%
LC4	1.84	5.47	13.17	7.31	15.01	0.00	7.70	0.00%
EX4	5.43	12.38	15.43	17.81	20.86	-0.00	3.05	19.30%
ST4	4.49	10.10	16.34	14.59	20.83	0.00	6.24	2.50%
LA4	5.56	20.93	20.97	26.49	26.53	0.00	0.03	94.90%
TE4	2.33	26.51	28.27	28.84	30.59	0.01	1.76	25.00%
BF4	4.56	28.85	30.63	33.41	35.19	1.78	1.78	25.30%
LC5	1.86	7.31	20.78	9.17	22.64	5.17	13.47	0.00%
EX5	3.53	17.81	23.28	21.34	26.81	5.18	5.47	2.60%
ST5	3.53	14.59	23.28	18.12	26.81	8.41	8.69	1.00%
LA5	5.53	26.53	26.81	32.06	32.34	0.01	0.28	74.40%
TE5	2.84	32.06	32.34	34.91	35.19	0.28	0.28	74.70%
BF5	1.83	35.19	35.19	37.01	37.01	0.00	-0.00	100.00%

Average Project Duration = 36.581

Std. Dev. Of Project Duration = 3.182

95% C.I. on Project Duration = [35.675 , 37.484]

4.5.5 CASE 5: Project Example with Skewed-to-Left Pert Distribution

This case used the skewed-to-left pert distribution for calculating the duration of different activities. Table 4.6a shows the results for this case using PERT method. Table 4.6b presents the results for this case using STROBOSCOPE. Source code of STROBOSCOPE for Case 5 is presented in the Appendix A. The total project duration from PERT came out to be in side 95% confidence interval of average project duration from simulation. PERT's project duration was –0.65 σ from simulation average project duration.

TABLE 4.6a : PERT Calculation for Project Example with Skewed-to-Left Pert Distribution

Activity	Predecessors	Probabilistic Duration	Expected Duration (a+4m+b)/6	ESD	EFD	Std dev σ = (b-a)/6	Var σ²	Crit Path
LC1	—	Pert[1,2.5,3]	2.33	0	2.33	1/3	1/9	Y
EX1	LC1	Pert[1,5,6]	4.5	2.33	6.83	5/6	25/36	Y
ST1	LC1	Pert[1,4,5]	3.66	2.33	6	2/3	4/9	
LA1	EX1, ST1	Pert[1,7,8]	6.16	6.83	13	7/6	49/36	Y
TE1	LA1	Pert[2,4,5]	3.83	13	16.83	1/2	1/4	
BF1	TE1	Pert[1,2.5,3]	2.33	16.83	19.16	1/3	1/9	
LC2	LC1	Pert[1,2.5,3]	2.33	2.33	4.66	1/3	1/9	
EX2	EX1, LC2	Pert[,1,4,5]	3.66	6.83	10.5	2/3	4/9	
ST2	ST1, LC2	Pert[1,4,5]	3.66	6	9.66	2/3	4/9	
LA2	LA1, EX2, ST2	Pert[2,8,9]	7.16	13	20.16	7/6	49/36	Y
TE2	TE1, LA2	Pert[2,4,5]	3.83	20.16	24	1/2	1/4	
BF2	BF1, TE2	Pert[1,2.5,3]	2.33	24	26.33	1/3	1/9	
LC3	LC2	Pert[1,2.5,3]	2.33	4.66	7	1/3	1/9	
EX3	EX2, LC3	Pert[1,5,6]	4.5	10.5	15	5/6	25/36	
ST3	ST2, LC3	Pert[1,4,5]	3.66	9.66	13.33	2/3	4/9	
LA3	LA2, EX3, ST3	Pert[1,7,8]	6.16	20.16	26.33	7/6	49/36	Y
TE3	TE2, LA3	Pert[2,4,5]	3.83	26.33	30.16	1/2	1/4	
BF3	BF2, TE3	Pert[1,4,5]	3.66	30.16	33.83	2/3	4/9	
LC4	LC3	Pert[1,2.5,3]	2.33	7	9.33	1/3	1/9	
EX4	EX3, LC4	Pert[2,8,9]	7.16	15	22.16	7/6	49/36	
ST4	ST3, LC4	Pert[2,4,5]	3.83	13.33	17.16	1/2	1/4	
LA4	LA3, EX4, ST4	Pert[2,8,9]	7.16	26.33	33.5	7/6	49/36	Y
TE4	TE3, LA4	Pert[1,4,5]	3.66	33.5	37.16	2/3	4/9	
BF4	BF3, TE4	Pert[2,4,5]	3.83	37.16	41	1/2	1/4	
LC5	LC4	Pert[1,2.5,3]	2.33	9.33	11.66	1/3	1/9	
EX5	EX4, LC5	Pert[1,4,5]	3.66	22.16	25.83	2/3	4/9	
ST5	ST4, LC5	Pert[1,4,5]	3.66	17.16	20.83	2/3	4/9	
LA5	LA4, EX5, ST5	Pert[2,8,9]	7.16	33.5	40.66	7/6	49/36	Y
TE5	TE4, LA5	Pert[2,4,5]	3.83	40.66	44.5	1/2	1/4	Y
BF5	BF4, TE5	Pert[1,2.5,3]	2.33	44.5	46.83	1/3	1/9	Y

TABLE 4.6b : Example Simulation Results for Project Example with Skewed-to-Left Pert Distribution and overall result for all runs

Number of replications performed : 50
Average Project Duration : 46.98
Std. Dev. of Project Duration : 2.70

CPM Activity	Time	ESD	LSD	EFD	LFD	FF	TF	%Critic
LC1	2.35	0.00	-0.00	2.35	2.35	0.00	-0.00	100.00%
EX1	4.49	2.35	2.48	6.84	6.98	0.00	0.14	79.30%
ST1	3.67	2.35	3.40	6.02	7.07	0.01	1.05	20.70%
LA1	6.14	6.98	7.10	13.12	13.24	-0.00	0.12	89.30%
TE1	3.85	13.12	24.98	16.97	28.83	-0.00	11.86	0.00%
BF1	2.33	16.97	32.42	19.30	34.75	4.86	15.45	0.00%
LC2	2.33	2.35	6.60	4.67	8.93	0.00	4.26	0.00%
EX2	3.66	6.84	9.25	10.50	12.91	0.00	2.41	9.70%
ST2	3.68	6.03	9.56	9.71	13.24	0.00	3.53	1.00%
LA2	7.18	13.16	13.24	20.34	20.42	0.00	0.08	93.70%
TE2	3.82	20.35	28.83	24.16	32.65	-0.00	8.48	0.00%
BF2	2.34	24.16	34.75	26.50	37.08	3.80	10.58	0.00%
LC3	2.34	4.67	12.16	7.01	14.49	0.00	7.48	0.00%
EX3	4.51	10.50	14.55	15.02	19.07	-0.00	4.05	6.30%
ST3	3.69	9.71	16.69	13.40	20.38	0.00	6.98	0.00%
LA3	6.06	20.34	20.42	26.40	26.48	0.01	0.08	93.80%
TE3	3.86	26.45	32.65	30.30	36.51	-0.00	6.20	0.20%
BF3	3.69	30.30	37.08	33.99	40.77	3.33	6.78	0.20%
LC4	2.33	7.01	16.98	9.34	19.31	-0.00	9.97	0.00%
EX4	7.17	15.02	19.31	22.19	26.48	-0.00	4.30	6.20%
ST4	3.84	13.40	22.64	17.24	26.48	0.00	9.24	0.00%
LA4	7.13	26.48	26.48	33.61	33.62	-0.00	0.00	99.80%
TE4	3.67	33.62	36.81	37.30	40.48	0.02	3.19	2.10%
BF4	3.81	37.32	40.77	41.13	44.58	3.46	3.46	1.80%
LC5	2.32	9.34	27.29	11.66	29.61	5.57	17.95	0.00%
EX5	3.65	22.19	29.97	25.84	33.63	7.78	7.79	0.00%
ST5	3.65	17.24	29.98	20.89	33.63	12.72	12.73	0.00%
LA5	7.13	33.61	33.63	40.75	40.76	0.00	0.01	97.70%
TE5	3.82	40.75	40.76	44.57	44.58	0.01	0.01	98.20%
BF5	2.34	44.58	44.58	46.92	46.92	0.00	-0.00	100.00%

Average Project Duration = 47.08

Std. Dev. Of Project Duration = 2.711

95% C.I. on Project Duration = [46.309 , 47.849]

4.6 Conclusions

After analyzing the results obtained from using PERT method and STROBOSCOPE simulation language, several facts were revealed.

In the cases discussed, total duration of project were nearly same by PERT as by simulation. This depicts that PERT is a good approximation as long as total duration is the only criteria. Another fact noticed was that in all cases except case2 and case 3, simulation showed more activities as critical than of PERT method. While the cause of similar activities being critical in case 2 and case 3 was the smaller ranges of duration of activities. Here one consideration should also be taken into account that this was a case of schedule with only one critical path.

Another fact noticed that PERT's responses were always came out lesser than the average response from simulation. In addition, it presented the fact that simulation gives additional information about activities that are critical or prone to be critical. This information cannot be provided using other methods e.g. PERT.

CHAPTER 5

SIMULATION OF STRINGING OF OVERHEAD TRANSMISSION LINE CONDUCTORS AND OVERHEAD GROUND WIRES

5.1 Introduction

Being the most economic way, direct earth buried cable laying has been standardized except where the cable route intersects streets and other utility mains. The major activities associated with direct buried cable installation are (1) trench excavation; (2) cable laying; (3) cable testing; (4) trench backfilling; and (5) surface reinstatement. Different procedures and resources can be used for the different activities.

5.1.1 Conductor Stringing Method

Conductor (including overhead ground-wire) stringing systems presently in use in the electric power industry are almost as numerous as the number of organizations that string conductor. Outlined here is the basic method currently in use that is modified to accommodate available equipment and the ideas and philosophy of the responsible supervisor. This basic method which will be explained here is the *TENSION METHOD*.

5.1.2 Tension Method

Using this method, the conductor is kept under tension during the stringing process. Normally, this method is used to keep the conductor clear of the ground and obstacles which might cause conductor surface damage and clear of energized circuits. It requires the pulling of a light pilot line into the travelers that in turn are used to pull in a heavier pulling line. The pulling line is then used to pull in the conductors from the reel stands using specially designed tensions and puller. For lighter conductors, a lightweight pulling line may be used in place of the pilot line to directly pull in the conductor. The method used for lighter conductor will be utilized for model development purpose as this is the most prevalent practice. A suitable ground vehicle can be used to pull or layout a pilot line or pulling lines. The tension method of stringing is applicable where it is desired to keep the conductor off the ground to minimize conductor surface damage, or in areas where frequent crossings are encountered. The amount of right-of-way travel by heavy equipment is also reduced. Usually, this method provides the most economical means of stringing conductor.

A typical crew to perform the conductor stringing operation using the tension method will generally consist of a general foreman, tensioner operator, puller operator, winder operator, conductor splicer, two tractor operators, two truck drivers, six linemen, and four ground-men. This crew will vary depending on equipment available to be used and also whether a circuit phase is one conductor, bundle two conductors, three conductors or four conductors. The crew for setting crossing structures will be the same as required for the slack or layout method. Major equipment required for tension

stringing includes reel stands, tensioner, puller, reel winder, pilot line winder, splicing cart, and pulling vehicle. Equipment for setting crossing structures requires a hole borer/digger, truck and pole trailer. *(SCECO CONSTRUCTION STANDARDS 1989)*

The aim of this work is to conduct a simulation study with different scenarios of the stringing of overhead transmission line conductors and overhead ground wires in order to provide general recommendation for the best scenario for use in future projects.

5.1.3 Scope of Work

This work will provide general recommendations for the selection of method, equipment and manpower for the stringing of overhead transmission line conductors and overhead ground wires using simulation. The project also will include wire-stringing terms most commonly used, and in addition, the tools and equipment required to complete the wire stringing operations. Moreover, sensitivity analysis of different factors will be presented individually.

5.1.4 Objective

The objective of this project is to estimate the time required to construct a certain length of overhead power line and to know the cost associated with that certain length. Moreover, this is also to present, in one document, sufficient details of presently used methods and materials for the practical and positive control of conductors during stringing operations.

The purpose of this project is to present sufficient details of presently used methods and materials for the practical and positive control of conductors during stringing operations. Also aim of this work is to conduct a simulation study with different scenarios of the stringing of overhead transmission line conductors and overhead ground wires in order to recommend the best method for use in future projects.

5.2 Simulation Approach

One often seeks optimal combination of factors that maximize or minimize a response. There are several ways for accomplishing the task as m*n replications, 2^k factorial design, 2^{k-p} fractional factorial designs, etc. These methods were found out to be of less interest to us, as they quickly turn infeasible in terms of computing time and power requirements. Instead, factors are varied individually from default value i.e. one, to four. Additionally, to check the reliablity of trends, runs are also performed with a maximum value of each factor as fifty 50. Pert[p0, mode, p100] distribution were used for defining activities duration, Where p0 represents most optimistic estimate, and p100 as most pessimistic estimate. Each experiment consists of ten 10-simulation runs, as came out through experimental design and the average total project duration and average total project cost was calculated. Each experiment was repeated ten times and average of all experiments for response, i.e. total duration of project and total cost of project, was calculated. Same procedure was repeated for all cases. Moreover, 95% confidence intervals for all responses were also established for all runs.

5.3 The Model

The model developed for the purpose is based on the practices prevalent in local construction industry. In its essence the method is a modification of the standard tension method which consists of three major phases, while the method used consist of two phases as it is the prevailant practice in construction industry. The details of standard tension method were provided previously under tension method heading. Here the elaboration of the model is being presented. The model follows the following sequence.

Pilot line winder operator unwinds the pilot line. GroundMen crew takes the pilot line to tower. Linemen crew takes the pilot line up to the tower. Pilot line passes over the tower through traveler to the other side of tower. After the pilot line passes over the tower, it goes to ground and wait to be connected to the tractor by GroundMen crew. Tractor travels 300 meters pulling the pilot line to the next tower. Then tractor waits to be disconnected from pilot line by GroundMen crew. GroundMen crew disconnects the pilot line from tractor. The tractor repositions itself and waits in a queue to be connected to pilot line for the next span of tower. After this process an inspection sequence is introduce to check that whether the length of the pilot lone has been reached to the required length. A supervisor checks and issues the order to continue the next span or to start the next phase. This concludes the phase one of model.

Phase two starts when supervisor issues the order to stop pulling the pilot line as it has reached the required length or in other words has reached to the last tower. Here pilot

line connects to the conductor by GroundMen crew. Winder starts pulling back the pilot line to its starting side. As the conductor is connected to the pilot line, it reaches the starting side as soon as pilot line is completely winded. Conductor is now over the steel tower and is now anchored. This concludes the second phase. In the similar way all three conductors are stringed over steel towers and installation completes.

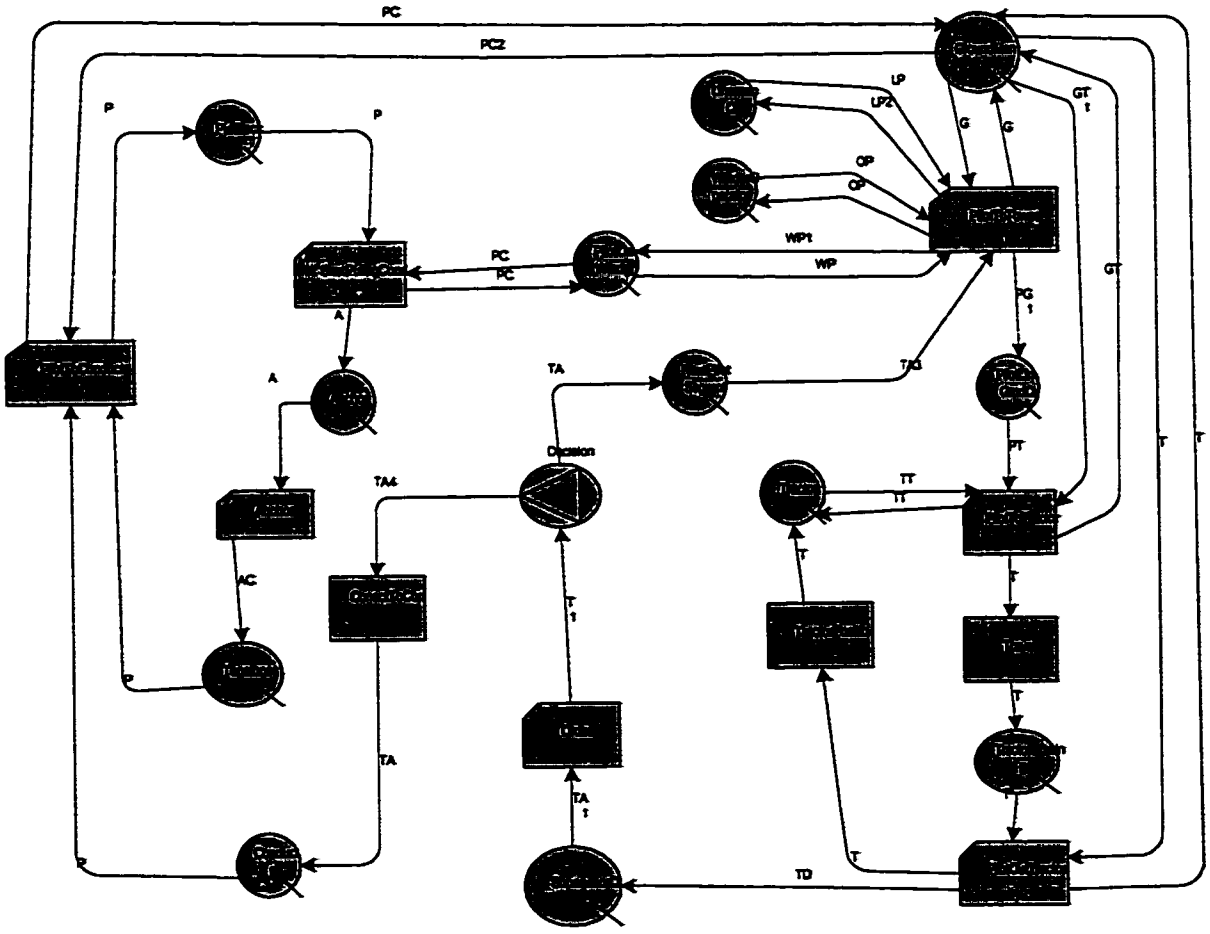

Figure 5.A: Graphical Representation of the Model

Figure 5.A presents the graphical representation of the model used for simulation purposes. It provides a means for understanding the process as well as the source code written in STROBOSCOPE discrete event simulation language. In addition to figure, explanatory statements are provided in the source code also provides detail help. Source Code of STROBOSCOPE for the model of example project is presented in Appendix B. Following is the data used in simulation model.

Total length of overhead power line = 5000 m

Number of Ground Men crews = 1

Number of Ground Men per crew = 4

Number of Line Men crews = 1

Number of Line Men per crew = 6

Number of Pilot Line Winders = 1

Number of Conductor Tensioners = 1

Number of Tractors = 1

Cost for Pilot line Winder = SR 250 /hr

Tractor Cost = SR 200 /hr

Conductor Tensioner Cost = SR 250 /hr

5.4 Results and Analysis

Several variables were identified during the development of model that could have different numbers and can effect the overall cost and/or duration of the model. Hence, changing the values of those variables linearly and individually were employed to study

the behavior of individual nature of these variable and also because of fact that combined factors runs seemed computationally infeasible.

A list of these variables is provided below

- Number of GroundMen Crews
- Number of LineMen Crews
- Number of Conductor Tensioner
- Number of Tractors
- Number of PilotLine Winders

In order to study the effects of individual factor, their values were changed from one 1 i.e. default value, to four 4. Additionally, average project duration and cost were also plotted for groundmen crew numbers of fifty 50, for checking as extreme value. Table 5.1 presents simulation results for all factors in terms of average, standard deviation and with 95% confidence interval of responses.

Table 5.1 : Simulation Results for all factors with 95% confidence Interval of Responses

Simulation Run Description	Average Project Duration	Std. Dev. of Project Duration	Confidence Interval Project Duration Lower	Confidence Interval Project Duration Upper	Average Project Cost	Std. Dev. of Project Cost	Confidence Interval Project Cost Lower	Confidence Interval Project Cost Upper
GroundMen Crews								
1	10417.05	3.92	10414.25	10419.85	7812785.0	2935.5	7810685.1	7814884.9
2	9998.06	3.95	9995.23	10000.88	7498542.3	2960.7	7496424.4	7500660.3
3	9859.22	3.31	9856.85	9861.59	7394413.6	2483.6	7392637.0	7396190.3
4	9789.80	4.10	9786.87	9792.73	7342352.7	3071.5	7340155.5	7344550.0
50	9599.14	4.43	9595.97	9602.30	7199351.2	3323.3	7196973.9	7201728.5
LineMen Crew								
1	10417.05	3.92	10414.25	10419.85	7812785.0	2935.5	7810685.1	7814884.9
2	10416.69	4.45	10413.50	10419.88	7812517.0	3342.6	7810125.9	7814908.2
3	10416.90	4.91	10413.39	10420.41	7812677.6	3679.7	7810045.3	7815309.9
4	10416.58	5.08	10412.95	10420.21	7812435.2	3809.9	7809709.8	7815160.6
50	10416.17	4.00	10413.30	10419.03	7812124.6	3003.9	7809975.7	7814273.5
Tensioners								
1	10417.05	3.92	10414.25	10419.85	7812785.0	2935.5	7810685.1	7814884.9
2	7917.70	3.88	7914.92	7920.47	5938273.3	2906.9	5936193.8	5940352.7
3	7916.93	4.15	7913.96	7919.90	5937699.0	3112.2	5935472.7	5939925.3
4	7917.84	3.86	7915.08	7920.59	5938377.7	2892.4	5936308.6	5940446.8
50	7917.06	4.03	7914.18	7919.95	5937799.0	3022.8	5935636.6	5939961.4
Tractors								
1	10417.05	3.92	10414.25	10419.85	7812785.0	2935.5	7810685.1	7814884.9
2	10415.78	3.57	10413.23	10418.34	7811837.6	2677.4	7809922.3	7813752.9
3	10417.32	4.69	10413.97	10420.68	7812993.1	3516.4	7810477.6	7815508.6
4	10416.19	4.28	10413.13	10419.25	7812141.6	3207.6	7809847.1	7814436.2
50	10416.65	3.38	10414.23	10419.07	7812486.3	2534.6	7810673.2	7814299.4
PilotLine Winders								
1	10417.05	3.92	10414.25	10419.85	7812785.0	2935.5	7810685.1	7814884.9
2	10417.40	4.08	10414.49	10420.33	7813054.2	3061.2	7810864.4	7815244.1
3	10416.61	3.89	10413.83	10419.39	7812455.2	2914.4	7810370.4	7814540.0
4	10416.43	3.70	10413.79	10419.08	7812324.6	2775.2	7810339.4	7814309.8
50	10416.67	4.07	10413.75	10419.58	7812500.0	3055.6	7810314.2	7814685.9

Below are the presentation of results for each variable and its analysis.

5.4.1 GroundMen Crews

Figure 5.1.a presents the pattern of change while changing the number of GroundMen crews from one to four, on total duration of project. This was accomplished by plotting the average Total duration of project against Number of GroundMen crews. *Figure 5.1.b* presents the results while changing the number of GroundMen crews from one to four on Total cost of project. This was accomplished by plotting the average Total cost of project against Number of GroundMen crews. Additionally, Average project duration and cost were also plotted for groundmen crew numbers of fifty 50, for checking as extreme value.

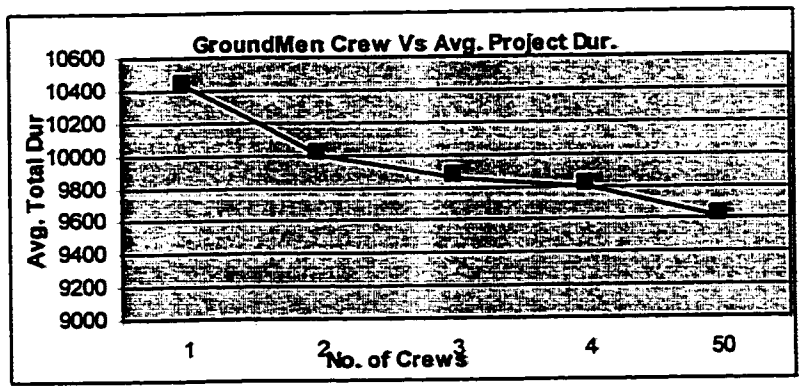

Figure 5.1.a: Total Duraiton Vs No.of GroundMen Crews Plot

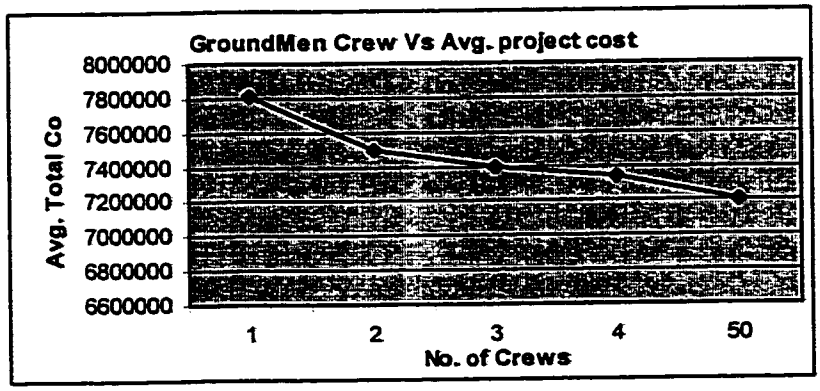

Figure 5.1.b: Total Cost Vs No. of GroundMen Crews Plot

5.4.2 LineMen Crews

Figure 5.2.a presents the pattern of change while changing the number of LineMen crews from one to four on total duration of project. This was accomplished by plotting the average Total duration of project against Number of LineMen crews. *Figure 5.2.b* presents the pattern of change while changing the number of LineMen crews from one to four on Total cost of project. This was accomplished by plotting the average Total cost of project against Number of LineMen crews. Additionally, Average project duration and cost were also plotted for groundmen crew numbers of fifty 50, for checking as extreme value.

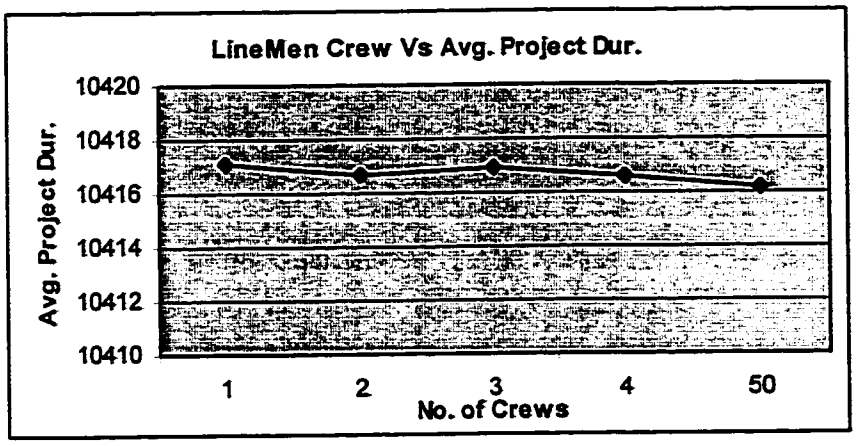

Figure 5.2.a: Total Duration Vs No.of LineMen Crew

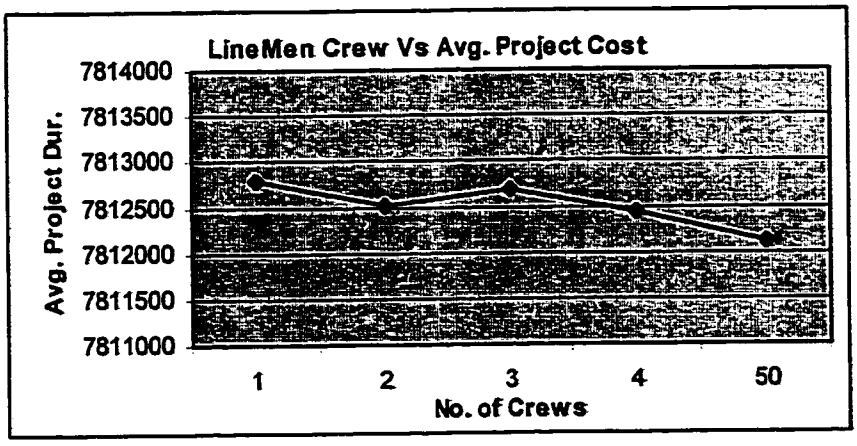

Figure 5.2.b: Total Cost Vs No.of LineMen Crew

5.4.3 Conductor Tensioners

Figure 5.3.a presents the pattern while changing the number of Conductor Tensioner from one to four, on Total duration of project. This was accomplished by plotting the average Total duration of project against Number of Conductor Tensioner. *Figure 5.3.b* presents the pattern on Total cost of project. Additionally, Average project duration and cost were also plotted for groundmen crew numbers of fifty 50, for checking as extreme value.

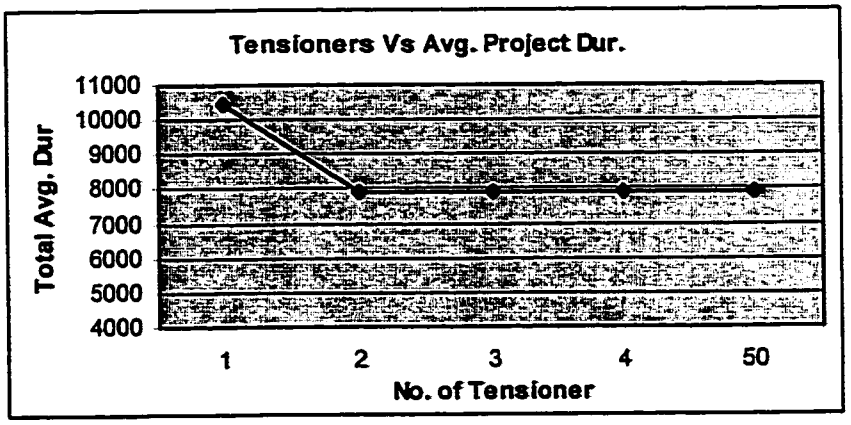

Figure 5.3.a: Total Duration Vs No.of Conductor Tensioner

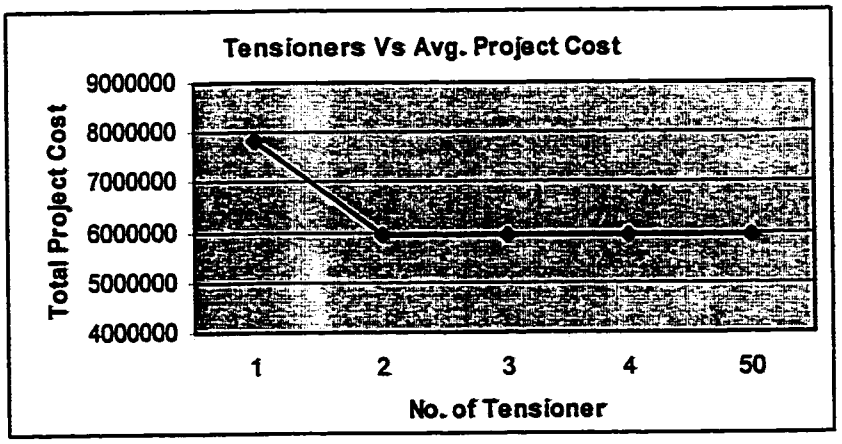

Figure 5.3.b: Total Cost Vs No.of Conductor Tensioner

5.4.4 Tractors

Figure 5.4.a presents the pattern of change while changing the number of Tractor from one to four on Total duration of project. This was accomplished by plotting the average Total duration of project against Number of Tractor. *Figure 5.4.b* presents the pattern of change while changing the number of Tractor from one to four on Total cost of project. This was accomplished by plotting the average Total cost of project against Number of Tractor. Additionally, Average project duration and cost were also plotted for groundmen crew numbers of fifty 50, for checking as extreme value.

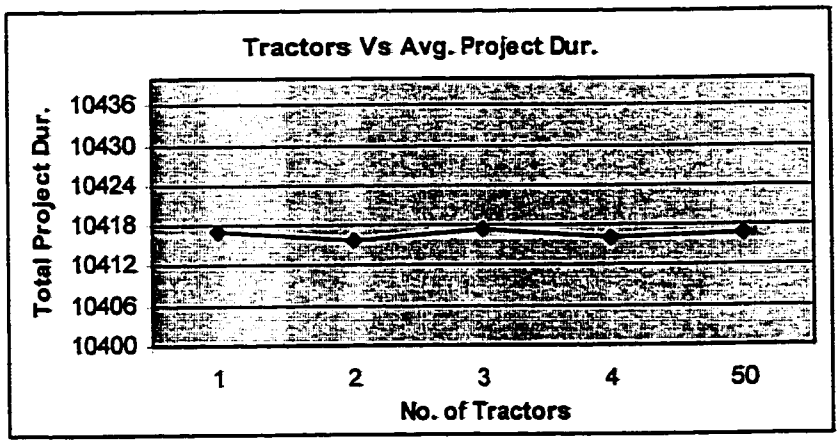

Figure 5.4.a: Total Duration Vs No.of Tractors

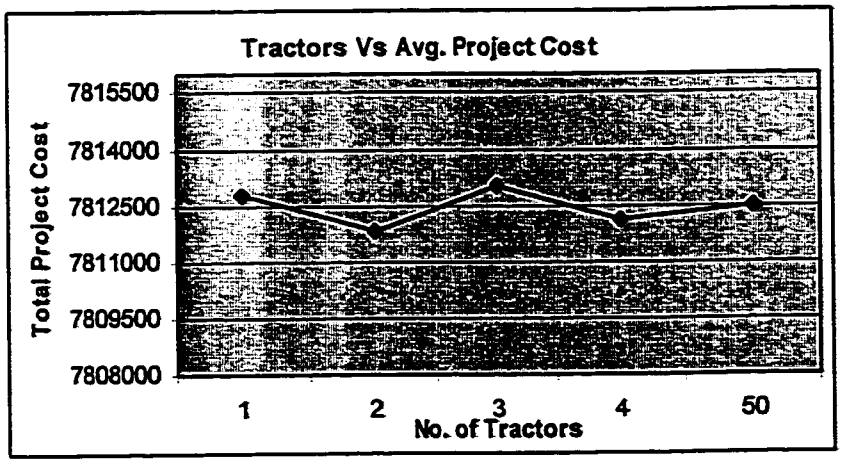

Figure 5.4.b: Total Cost Vs No.of Tractors

5.4.5 PilotLine Winders

Figure 5.5.a presents the pattern of change while changing the number of PilotLine Winders from one to four on Total duration of project. This was accomplished by plotting the average Total duration of project against Number of PilotLine Winders. *Figure 5.5.b* presents the pattern of change for Total cost of project. This was accomplished by plotting the average Total cost of project against Number of PilotLine Winders. Additionally, Average project duration and cost were also plotted for groundmen crew numbers of fifty 50, for checking as extreme value.

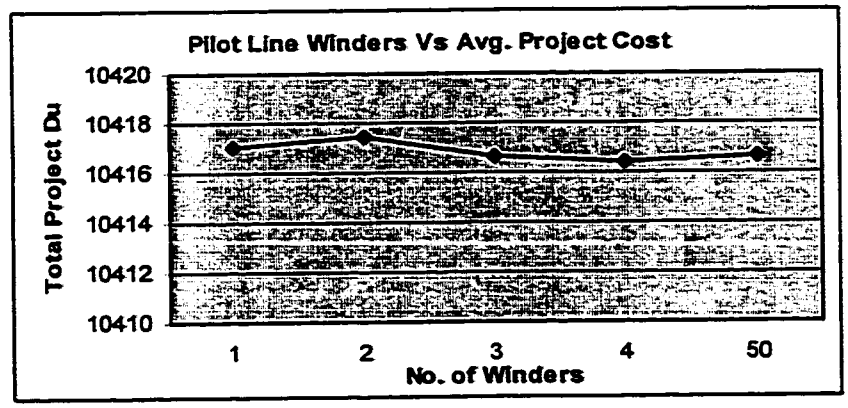

Figure 5.5.a: Total Duration Vs No. of Winders

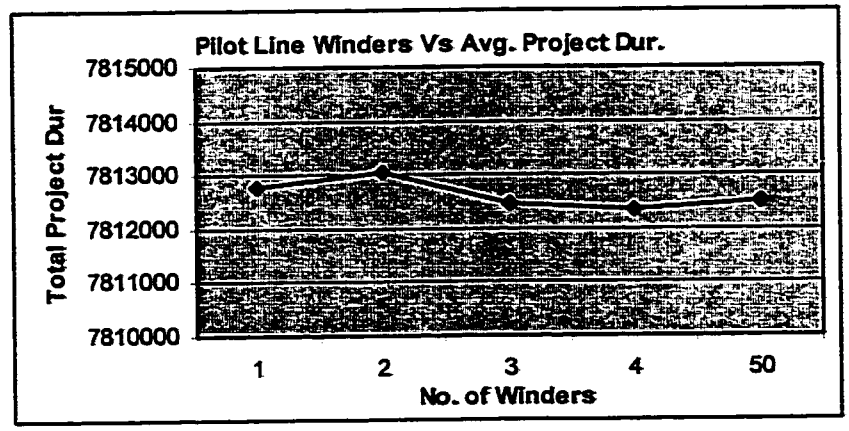

Figure 5.5.b: Total Cost Vs No. of Winders

For interpretation of the trends, combined graphs for all variables provides overall picture in term of change in duration and cost, as in Figure 5.6.a and 5.6.b.

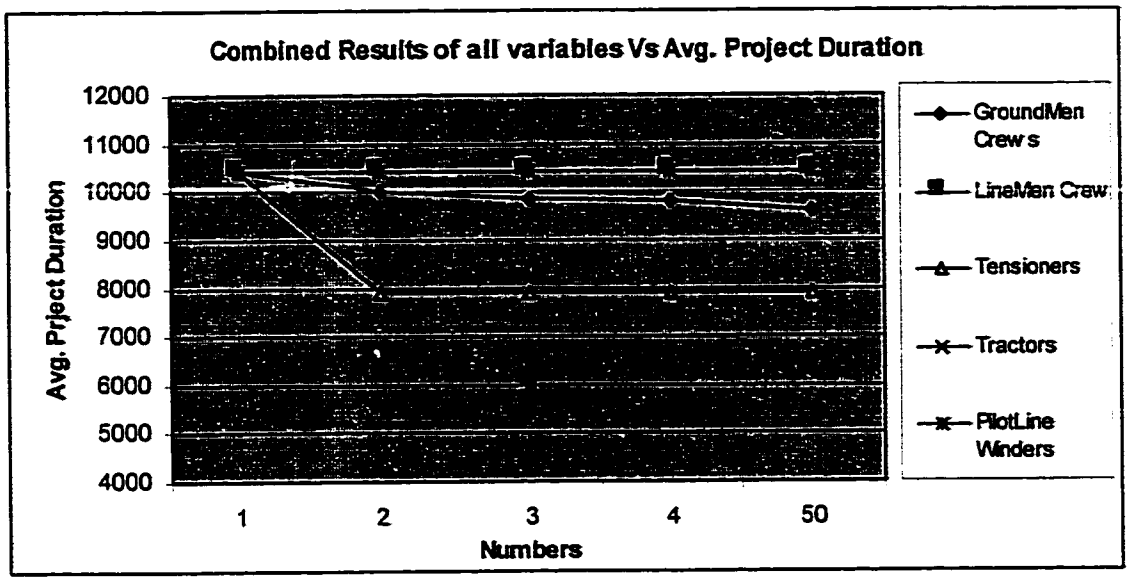

Figure 5.6.a: Combined Results of all Variables Vs Duration

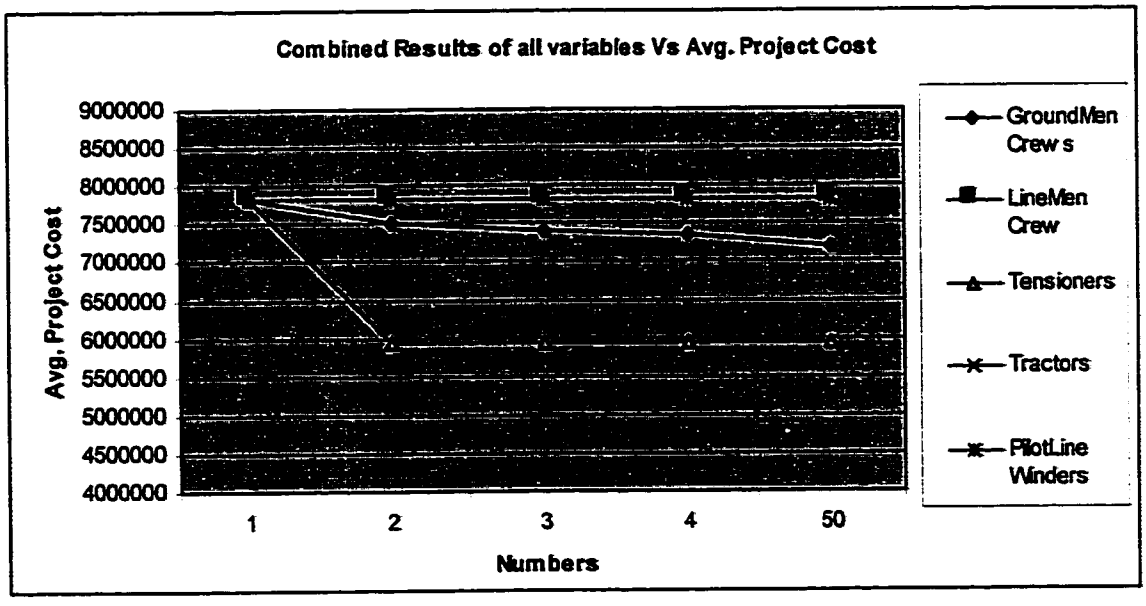

Figure 5.6.b: Combined Results of all Variables Vs Cost

5.5 Conclusions

The example project presented in this work illustrates STROBOSCOPE's power as a general-purpose simulation system. Complex and realistic problems such as the example presented can be modeled, analyzed and optimized quite easily.

The result shows that not all the variables affect the total duration and cost of the project, within the scope of study. Figure 5.1.a to Figure 5.5.a represented the pattern of change in average total duration of the project for different variables individually. Figure 5.1.b to Figure 5.5.b depicted the pattern of change in average total cost of the project for different variables individually. Within the scope of study, groundmen crew variable came out to be affecting the cost and duration of project as by adding crew, total duration, and in turn cost, continues to drop. Project's duration and cost, decreased when number of Tensioner increased till two, but showed no effect afterwards while increasing number of Tensioner. Other variables did not show any significant change in the project's cost and duration. For further help in interpretation of the trends, combined graphs for various variables can be used as in Fig. 5.7.a and 5.7.b. The results can provide a foundation for decision making. In absence of actual data for total project duration and cost for all cases, the compaison can not be made.

CHAPTER 6

SIMULATION OF TIME-COST TRADEOFF FOR THE CONSTRUCTION OF FLOW LINE PIPES

6.1 Introduction

Construction Simulation is a powerful tool that can be used for a number of tasks such as productivity measurement, risk analysis, resource planning, design and analysis of construction methods, site planning and like wise tasks. The advent of simulation methods in construction occurred in the form of simple modeling framework for studying construction operations. The success of simulation at the construction process level has led to natural attempt to use simulation at the construction project level. The objective of this approach is to allow development of models that combine all the process and link them to simulate them on a higher level. Such a simulation experiment will allow the construction manager to realistically model, analyze, and plan construction projects.

In a process-level analysis the modeler selects a process that is part of a construction project and simulate it. In this type of simulation experiment, it is assumed that the process is not effected by other processes on the project. Normally a construction project can be viewed as a collection of processes. Based on the implementation strategy adopted these processes are linked together.

Optimizing schedule is an important task, but it is difficult to play its effective role in practice since there is no effective optimization method used in practice. In practice, however, project managers usually need to consider many factors in scheduling, and the optimization method of construction schedule is needed even when the total duration is determined. In fact, the economic effectiveness of a construction project is closely influenced by many factors. The project manager, for instance, may wish to shorten the duration of the investment so as to improve project economic benefit by decreasing the final amount of investment; he or she also wants to consider the seasonal weather variations that may affect productivity and wants to supply resources evenly to improve project economic benefit.

6.1.1 Objectives

This study, aims at use project-level simulation as an optimizing strategy to obtain the discussed objectives. By providing a basis for optimizing, this will basically use simulation for planning / decision making from management perspective while process-level simulation still provides a mean for making decision from lower level construction perspective. This will also introduce STROBOSCOPE as a planning / decision making tool besides its significance as process level simulation tool.

6.1.2 Scope of Work

The study is essentially an attempt to use project level simulation as planning tool for flow line piping construction. It deals with cost and duration concerns of the project. Therefore, the resources allocation is taken care of in terms of overall cost of that activity. Additionally it employees CPM network for sequencing of the activities and project planning, and stroboscope as simulation engine for that CPM network. If the project sequencing requires project's network definition technique other than CPM, then the methodology employed in this work might not be valid in its current form.

6.2 Pipeline Construction

Pipeline construction in general has developed into a highly specialized industry. The building of lines to transport petroleum and natural gas employs equipment and practices, many of which are unused, even unknown, in other segments of the construction field *(Bell 1963)*. Piping systems of petrochemical plants are complex and large. A piping system has many spools, valves, and pumps that are connected to function as a processing unit. For some piping systems, there may be thousands of piping items with some as long as 150ft and weighing hundreds of tons. Others may be smaller than a person's fingernail *(Kim and Ibbs 1995)*.

6.2.1 Types of Pipelines

Most oil and gas pipelines fall into one of the three groups: gathering, trunk/transmission, or distribution. Other pipelines are needed in producing fields to inject gas, water, or other fluids into the formation to improve oil and gas recovery and to dispose of salt water often produced with oil *(Kennedy 1984)*. Generally, there are four types of pipelines; Flow Lines, Gathering Lines, Crude Trunk Lines, and Products Pipelines. Following is the brief discussion of these types.

6.2.1.1 Flow Lines

Flow lines, the first link in the transportation chain from producing well to consumer, are used to move, produced oil from individual wells to a central point in the field for treating and storage. Flow lines are generally small-diameter pipelines operating at relatively low pressure. The size required varies according to the capacity of the well being served, the length of the line, and the pressure able at the producing well to force the oil through the line. In many fields around the world, high-capacity wells require larger-diameter pipelines. Individual oil flow lines are relatively short, typically ranging from less than mile to a few miles. However, an oil field containing many wells, each of which is connected to central facilities by a flow line, can contain several hundred miles of pipeline in a relatively small geographical area. Flow lines are normally made of steel, though various types of plastic pipe have been used in a limited number of applications. Sections or joints, of steel pipe for flow lines can be connected by welding or by the use of threaded couplings. Other specialty joints and joining methods aimed at reducing

construction time and cost have also been developed for both steel and other flow-line materials *(Kennedy 1984)*.

6.2.1.2 Gathering Lines

Gathering lines is the next link in the oil pipeline chain that transport oil from field-processing and storage facilities to a large storage tank or tank farm where it is accumulated for pumping into the long-distance crude trunk line. These gathering systems are normally owned by the Pipeline Company that operates the main trunk line. Size, of course, depends on the volume of crude to be moved, pipeline length, and other factors. Operating pressure is higher than that of field flow lines. Gathering system throughput varies widely, depending on the number of field storage tanks served and the producing capacity of the wells in each field *(Kennedy 1984)*.

6.2.1.3 Crude Trunk Lines

Crude trunk lines move oil from large central storage facilities of producing areas to refineries for processing or to other storage terminals. This network of crude trunk lines comprises a variety of pipe sizes and capacities. Pumps are required at the beginning of the trunk line, and pumping stations must also be spaced along the pipeline to maintain pipeline pressure at the level required to overcome friction, changes in elevation, and other losses. Crude trunk lines operate at higher pressures than field-gathering systems and are also made of steel. Individual sections are joined by welding *(Kennedy 1984)*.

The complexity of these systems varies so widely that it is difficult to select a typical system. The fact that they travel long distances complicates their construction and operation. Flow lines are usually confined to a single field, and the parties involved in the decision making and permitting are few. In cases where a line must cross-land owned by many different owners, most of whom receive no benefit from the pipeline, only the job of obtaining right of way, for example, becomes significant.

6.2.1.4 Products Pipelines

The industry's products pipeline system, especially in the United States, is a sophisticated transportation network. Many segments of the system are highly flexible in both capacity and the products that can be transported. One part of this system moves refined petroleum products from refineries to storage and distribution terminals in consuming areas. Products shipped include the several grades of gasoline, aviation gasoline, diesel, and home heating oils. Another group of products pipelines is used to transport liquefied petroleum gases (LPG) and natural gas liquids (NGL) from processing plants in oil and gas-producing areas to refineries and petrochemical plants. In some cases, a mixed stream of liquid hydrocarbons separated from natural gas at field processing plants is moved to a fractionation plant where the mixed stream is separated into individual products. Products pipelines often must operate at higher pressures than crude pipelines because the material being transported is lighter than crude *(Kennedy 1984)*.

6.2.2 Construction Practices

Pipeline construction methods differ depending on the geographical area, the terrain, the environment, the type of pipeline, and the restrictions and standards imposed by governments and regulatory agencies. However, construction techniques can be broadly classified as land, offshore, and Arctic. The biggest differences exist between land construction (including Arctic) and offshore construction *(Kennedy 1984)*.

Construction costs also vary according to location, line size, environmental conditions, equipment required, and the construction schedule. Considering all types of pipeline construction, construction costs account for about 40% of the total investment in a pipeline system. In general, construction of a pipeline on land is the least expensive of the three types. Despite many differences, all pipeline construction projects have a number of features in common:

- The methods of designing the system—arriving at the optimum pipe diameter, determining the amount of horsepower required for pumping or compression, and meeting safety standards—are similar for all pipelines.
- There are a number of design criteria that are set by government or regulatory agencies to insure safe operation of a pipeline and the safety of personnel and property near the pipeline. These standards vary depending on the location of the pipeline, both geographically and in relation to populated areas and other facilities.

- Most oil, gas, and products pipelines are constructed by welding short lengths, or *joints,* of pipe together. There are a few exceptions to the use of welded connections, but these are in short lines within a producing field or in similar applications.
- Extensive testing of welders and the welds they produce is an important part of the construction of all long-distance petroleum pipelines.
- Almost all oil and gas pipelines are buried below ground level; even most offshore pipelines are buried below the seabed for protection. There are cases in which large segments of a major pipeline are not buried
- All pipelines are tested for leaks following construction before the line is put in service. Several techniques can be used, but the most common is hydrostatic testing—filling the line with water and subjecting it to a pressure greater than the design operating pressure.
- Most pipelines are coated on the exterior to prevent corrosion. Offshore pipelines are also "weight-coated" with a concrete coating to overcome the force of buoyancy and to prevent the pipe from floating to the surface.
- Most pipelines must have one or more pumping stations or compressor stations along the route to provide energy to overcome pressure loss and keep the fluid in the pipeline moving.

The construction of all pipelines follows this general sequence: design and route selection, obtaining rights of way, installation, tie-in to origin and destination facilities and pumping or compressor stations, and testing *(Kennedy 1984, Bell 1963)*.

Major pipeline projects are built by pipeline construction contractors rather than by the company that will own and operate the system. Typically, several contractors are invited to submit bids on the work. More than one contractor may be involved in a single large pipeline project to speed completion of the line. In addition, a number of other firms are involved to supply pipe and equipment and to perform special services such as pipe coating.

6.2.3 Flow line Construction

To find out the practices and sequence of work activities involved in flowline pipes construction, a number of professionals and specialists were interviewed from oil/gas industry of Saudi Arabia by the writer. It was concluded from gathered information that the actual installation of the pipe for a flow line includes these major segments:

- Survey and Layout
- Clearing the right of way (R.O.W) as needed
- Material delivery
- Fabricating and Installing Portable Pipe Support (P.P.S).
- Fabricating and Installing Well Head (W/H) and Tie-in Pipe Spools
- Fabricating and Constructing Removable Anchors
- Fabricating and Installing Cathodic Protection (CP) and Test station support
- Fabricating and Installing Guard Rail and Kilometer (KM) markers

- As-built Drawings
- Stringing pipe joints along the right of way
- Welding the pipe joints together
- Paint/Sand blasting
- Road and Camel Crossing
- Testing the line for leaks (Hydro-testing)
- Clean-up and Punch list

6.3 Project Level Simulation

The primary objective during the construction process is completing the project on time and within the budget while meeting established quality requirements and other specifications. To do so requires a substantial focus on forecasting duration and managing the construction.

Project cost is most sensitive to its schedule. The construction project environment comprising dynamic, uncertain, but predictable, variables such as weather, space congestion, workmen absenteeism, is changing continuously, affecting duration. A reliable forecast of the completion duration is one of the major concerns of a scheduling engineer. The reliability of project duration forecast can be enhanced by using simulation to determine the variations caused by the dynamic variables.

6.3.1 Need for Realistic Forecast of Project Completion Time

It is essential to have a reliable forecast of project completion time because of the following: *(Ahuja and Nandakumar 1985)*

- Many studies have revealed that it is possible to make relatively greater percentage of recovery if the potential delay is recognized earlier in the life of a project. The potential recovery decreases as one proceeds through the project until a time is reached when recovery is no longer possible. The early indication of delay through a reliable forecast allows decisions to be made in a less hectic environment.
- A delay in project completion can cause a cost escalation equal to the sum of inflation, overhead cost, and additional interest cost for the period. A realistic forecast gives a clear picture so alternative decisions involving time/cost tradeoff can be taken.
- In a production-oriented project, the marketability of the project is affected if its arrival on the market is delayed. Any delay in projects relating to infrastructure facilities upsets the economic feasibility of the projects that depends on them. An awareness of the project status through reliable forecast helps keep the project on schedule.

6.3.2 Time –Cost Trade off

In the business world it is imperative, or at least very desirable, to have a product on the market before the competitor does. Consequently, the criterion may be to maximize the probability of marketing it as early as possible while minimizing the increase in cost.

In network, planning the normal duration for each activity is specified; it is the time required to complete an activity with the resources normally available in the organization and with no extra inputs into the projects. Besides normal duration, normal cost is also specified. It is the estimated cost associated with normal duration. Normal cost may also be considered as simply the cost to the owner. It is possible to complete the activity in less time than scheduled. For example, by employing additional crew and incurring extra cost, the time required for form work can be reduced. This approach is known as "crashing". The crash duration and crash cost, however, must be known. The crash duration is the time, which is less than the normal duration time, required to complete an activity, possibly with extra funds or resources *(Harris 1978)*. The crash cost of an activity is the cost of completing an activity by its crash duration. Crash project duration is the time, which is less than the normal duration time, computed from a combination of crash and normal duration of activities to complete the project. Crash cost for project is the total cost associated with the crash project duration.

There are four types of relationships between the time and cost of an operation *(Ahuja et.al 1994)*.

1. Linear relationship between Time and Cost (Figure 6.1 a)

2. Multi-linear Cost-time relationship (Figure 6.1 b)

3. Discrete Cost-Time relationship (Figure 6.1 c)

4. Curvilinear Continuous Cost-Time relationship (Figure 6.1 d)

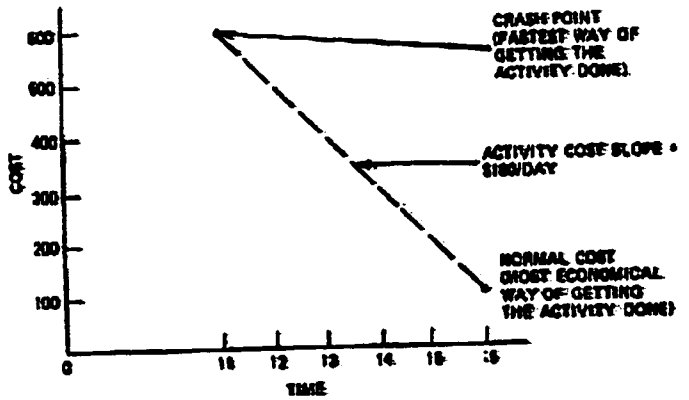

Figure 6.1 a : Linear Relationship between Time and Cost

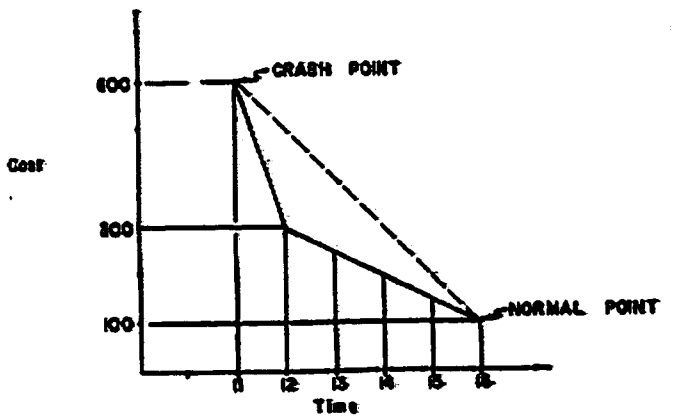

Figure 6.1 b : Multi linear Cost-Time Relationship

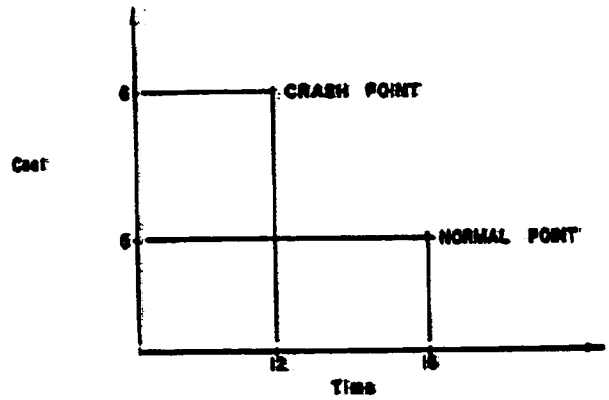

Figure 6.1 c : Discrete Cost-Time Relationship

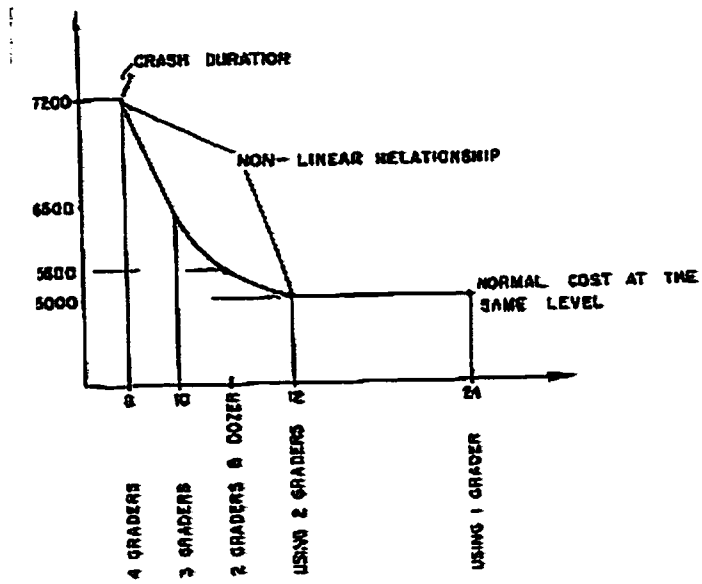

Figure 6.1 d: Curvilinear Continuous Cost-Time Relationship

Cost slope is the amount of funds required to reduce the duration of an activity by one day and calculated by

$$CostSlope = \frac{CrashCost - NormalCost}{NormalDuration - CrashDuration}$$

6.3.2.1 Procedure for Compression of Project Duration

Following are the steps for compression of project duration with normal start *(Ahuja et.al 1994)*.

1. Determine normal project duration and normal project cost
2. Identify normal duration critical path
3. Eliminate all non-critical activities that do not need to be crashed.
4. Tabulate normal and crash durations and normal and crash costs for all the activities
5. Compute and tabulate the cost slope of each activity form the following formula:
6. Proceed to determine the project time cost curve by shortening the critical activities beginning with the activity having the lowest cost slope. Each activity is shortened until (a) its crash time is reached or (b) a new critical path is formed
7. When a new critical path is formed, shorten the combination of activities having the lowest combined slope.
8. At each step check to see whether float time has been introduced in any of the activities. If so, perhaps these activities can be extended to reduce cost.
9. At each shortening cycle, compute the new project cost and duration. Tabulate and plot these points on a time-cost graph.
10. Continue until no further shortening is possible. This is the crash point.

6.3.2.2 Criteria for Minimum Cost Curve from Normal Start

The main object to be met in developing the project's minimum direct cost curve from the normal time-cost point is to shorten the project duration at the least possible increase in cost. In the selection of activities to achieve this objective there are three conditions to be satisfied *(Harris 1978)*.

1. The activity or activities must be critical and, if shortened, must shorten all existing critical paths
2. The activity or activities must have the smallest current cost slope
3. The activity or activities must be currently available for shortening. That is, they must have some remaining ΔT value.

6.4 Model Description

To illustrate the concepts for STROBOSCOPE utilization as a planning tool on project level, an example project was used. It is a project for flow line pipes construction. Following are the details of project and approaches taken.

6.4.1 Example Project

A flow line project was used for modeling purpose. This project is 14000 ft (2.652 miles) long and is for the 10" diameter pipeline. Table 6.1 presents the details of the project used. It shows the activities, their normal duration, crashed duration, normal cost of the activity, and cost of that activity with crashed duration. Though, the data used are based on multiple projects, but it does not represent any specific project. Hence, it is taken as a typical project.

The example data, that is not specific to any one project, was collected from industry sources. This data represents the typical activities and their average duration along with average costs. Figure 6.2 presents the CPM diagram of the example model describing relationship between activities as activity-on-node (A-O-N) form. CPM does not have the ability to define other than finish-to-start (FTS) relationship. To make it suitable for the purpose, it was necessary to define STS relationships, therefore few dummy activities were introduced to achieve the task.

Table 6.1: Example Project's activity duration and cost data

Activity ID.	Activity Description	Normal Dur. (days)	Crashed Dur. (days)	Normal Cost (per day)	Crashed Cost (per day)
A10	Mobilization	14	14	2000	2000
A20	Survey & Layout	14	10	12000	23000
A30	Material Delivery	21	15	6100	10200
A40	Fabricate P.P.S.	24	24	11900	11900
A50	Fabricate W/H and tie-in Pipe	28	28	24200	24200
A60	Fabricate Removable Anchor	20	20	12000	12000
A70	Construct R.O.W.	28	21	24000	39500
A80	Install P.P.S.	14	10	12100	23000
A90	Construct Removable Anchor	20	14	15100	29800
A100	Fabricate CP & Test Station	12	12	6000	6000
A110	Fabricate Guard Rail	10	10	9200	9200
A120	Fabricate KM Marker	7	7	5900	5900
A130	Sand Blast /Paint	10	6	11200	24600
A140	As-built Drawing	38	38	4100	4100
A150	Stringing	7	4	17600	38800
A160	Pipe Welding	21	15	25400	44600
A170	Install W/H Pipe Spool	14	14	17900	17900
A180	Road and Camel Xing	21	21	24100	24100
A190	Tie-in Pipe Spool	10	7	12800	19600
A200	Install Guard Rail & KM Marker	6	4	12000	22000
A210	Install CP / Test Station	14	14	5900	5900
A220	Hydro test	6	6	23800	23800
A230	Final Tie-in	4	4	11500	11500
A240	Clean-up & Punch list	7	7	11700	11700
A250	Final Paint	6	4	6000	11700
A260	Demobilization	7	7	3000	3000
D1	Dummy Activity	0	0	0	0
D2	Dummy Activity	7	7	0	0
D3	Dummy Activity	11	11	0	0

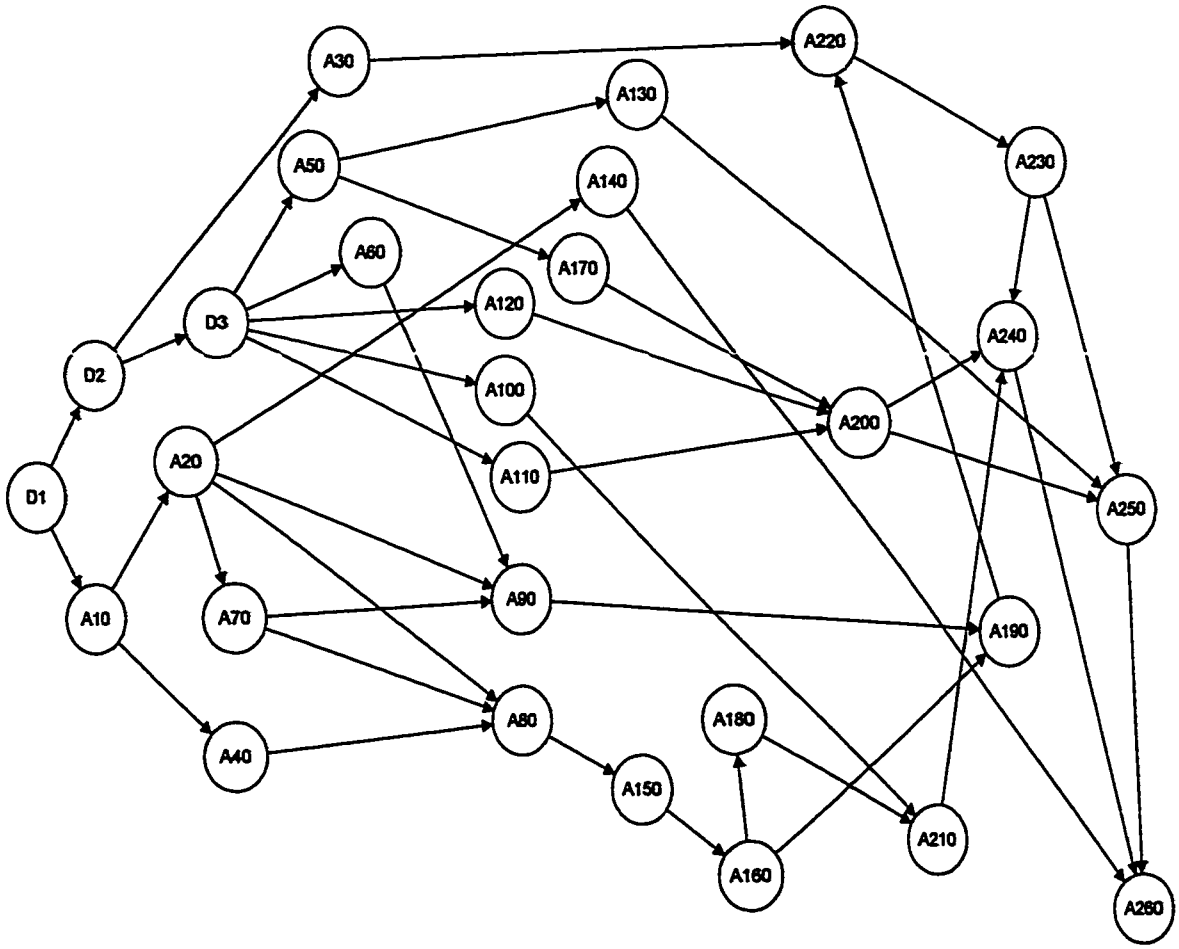

Figure 6.2 CPM diagram of the example Model

6.4.2 Methodology Adopted

The basic strategy adopted was to solve the model network using conventional method and then using STROBOSCOPE simulation for the same model. There are several conventional methods available for time-cost adjustments *(Harris 1978)*, but the most popular method amongst practitioner was used i.e. minimum cost curve from normal start. The second step of the work is to develop and run a STROBOSCOPE simulation of

the model. Afterwards, analysis of both approaches reveals cons and pros. Every research methodology has its restraints. Several limitations were observed during this work. Following are the major concerns about the work, which also defines the scope of the work.

6.4.3 Simulation Approach

In the task under study, CPM Add-on was used to model the network. This Add-on allows to define CPM networks with stochastic duration and to obtain various statistics about the project and its activities. The CPM network to be modeled does not have to have a single starting activity and single finishing activity (a common CPM requirement). The CPM Add-on precedes every network with a dummy START and concludes it with a dummy FINISH.

Since CPM-addon defines relationships as Finish-to-Start (FTS), so activities that have other relationships as Start-to-Start (STS) or Finish-to-Finish (FTF) can not be defined utilizing CPM add-on. In the project under consideration, many activities can best be defined with STS relationship. To overcome this shortcoming several dummy activities were introduced with duration equal to the lag between activities having STS relationship. By employing these dummy activities, it was made possible to have CPM with STS relationships.

In simulation, experimental design provides a way of deciding before the runs are made which particular configuration to simulate so that the desired information can be obtained with the least amount of simulating. One often seeks optimal combination of factors that maximize or minimize a response. There are multiple ways for accomplishing the task as m*n replications, 2^k factorial design, 2^{k-p} fractional factorial designs, etc. These conventional methods were found out to be of less interest to us, as they quickly turn infeasible in terms of computing time and power requirements. This happening can be understood by taking into account the fact that there were twenty-six (26) activities in total from which eleven (11) activities were possible to crash i.e. reduce their duration by enhancing the total resources represented in terms of cost. Using, for example, 2^k factorial design there are 2048 runs required. Each runs takes about eleven (22) seconds on the machine being used i.e. 350MHZ PII with 64 MB RAM, that concludes to 12.52 hours of computing effort. One can easily foresee the difficulties in this approach, as with the increase in number of activities there is an exponential increase in computing time required. For example, in case of twenty-six (26) activities, 17087.9 days of computing are required which makes it infeasible. While the same results can be achieved by some thirteen (13) runs, for eleven activities case. This was possible because of the CPM network that is quite different from other process networks.

Pert[p0, mode, p100] distribution were used for defining activities duration, Where p0 represents most optimistic estimate, and p100 as most pessimistic estimate. Each experiment consists of thirty 30-simulation runs, as came out through experimental design and the average total project duration and average total project cost was

calculated. Each experiment was repeated ten times and average of all experiments for response, i.e. total duration of project and total cost of project, was calculated. Same procedure was repeated for all cases. Moreover, 95% confidence intervals for all responses were also established for all runs.

In the approach used, first one run was made using normal duration of all activities. Then, one activity was crashed fully in each simulation run. Hence, eleven runs gave the fully compressed network. After observing the trends of project cost and duration from these simulation results, one additional runs was made crashing only those activities that were affecting the duration in previous run.

6.4.4 Source Code

Source code for the simulation run of the model can be found in Appendix C. The source code can provide means to make it run for all twenty-six activities crashing with modification, instead of the presented example case, where eleven activities were crashed.

6.5 Results and Analysis

The following discussion presents the results achieved from both the conventional method and simulation, and their analyses. Since there were two approaches for the solution of the model, this section is divided into two sub sections; first provides

information regarding conventional method used and second is specific to STROBOSCOPE simulation results.

6.5.1 Time-Cost Trade-off by Conventional Method

Initially, different aspects of the model project were calculated for normal conditions e.g. total cost, duration. Then by utilizing the procedure described in previous section, compression of project duration is achieved and corresponding costs were calculated. Table 6.2 shows the details of activities' normal and crashed duration and their respective costs, in addition to cost slope of the activities. While Table 6.3 presents the summary of crashing cycles and resulting cost and duration for the project.

In order to make the interpretation of results simpler and to view the trends visually instead in terms of numbers, several graphs are plotted. Figure 6.3 display graph between activities crashing and respective project costs. Figure 6.4 presents graph between activities crashing and their respective project duration. To give an overall impression of time-cost trade-off, Figure 6.5 exhibits trend between project duration and their respective costs.

Table 6.2: Details of activities normal and crashed duration and their respective costs

Activity ID	Activity Description	Normal Dur	Crashed Dur	Normal Cost	Crashed Cost	DT = TN-TC	Slope
		(days)	(days)				
A10	Mobilization	14	14	28000	28000	0	
A20	Survey & Layout	14	10	168000	230000	4	15500.0
A30	Material Delivery	21	15	128100	153000	6	4150.0
A40	Fabricate P.P.S.	24	24	285600	285600	0	
A50	Fabricate W/H and tie-in Pipe	28	28	677600	677600	0	
A60	Fabricate Removable Anchor	20	20	240000	240000	0	
A70	Construct R.O.W.	28	21	672000	829500	7	22500.0
A80	Install P.P.S.	14	10	169400	230000	4	15150.0
A90	Construct Removable Anchor	20	14	302000	417200	6	19200.0
A100	Fabricate CP & Test Station	12	12	72000	72000	0	
A110	Fabricate Guard Rail	10	10	92000	92000	0	
A120	Fabricate KM Marker	7	7	41300	41300	0	
A130	Sand Blast /Paint	10	6	112000	147600	4	8900.0
A140	As-built Drawing	38	38	155800	155800	0	
A150	Stringing	7	4	123200	155200	3	10666.7
A160	Pipe Welding	21	15	533400	669000	6	22600.0
A170	Install W/H Pipe Spool	14	14	250600	250600	0	
A180	Road and Camel Xing	21	21	506100	506100	0	
A190	Tie-in Pipe Spool	10	7	128000	137200	3	3066.7
A200	Install Guard Rail & KM Marker	6	4	72000	88000	2	8000.0
A210	Install CP / Test Station	14	14	82600	82600	0	
A220	Hydro test	6	6	142800	142800	0	
A230	Final Tie-in	4	4	46000	46000	0	
A240	Clean-up & Punch list	7	7	81900	81900	0	
A250	Final Paint	6	4	36000	46800	2	5400.0
A260	Demobilization	7	7	21000	21000	0	
				5167400	5826800		

Table 6.3 : Summary of crashing cycles and resulting cost and durations for the project

Combinations		Delta T		Days	SR	SR	Project Cost	Project Dur.
1	2	1	2	Changed	Slope	Changed		
Normal		0		0	0.0	0	5167400	147
A150		3		1	10666.7	10666.7	5178066.7	146
A150		2		1	10666.7	10666.7	5188733.4	145
A150		1		1	10666.7	10666.7	5199400	144
A80		4		1	15150.0	15150	5214550	143
A80		3		1	15150.0	15150	5229700	142
A80		2		1	15150.0	15150	5244850	141
A80		1		1	15150.0	15150	5260000	140
A20		4		1	15500.0	15500	5275500	139
A20		3		1	15500.0	15500	5291000	138
A20		2		1	15500.0	15500	5306500	137
A20		1		1	15500.0	15500	5322000	136
A70		7		1	22500.0	22500	5344500	135
A70		6		1	22500.0	22500	5367000	134
A70		5		1	22500.0	22500	5389500	133
A70		4		1	22500.0	22500	5412000	132
A70		3		1	22500.0	22500	5434500	131
A70		2		1	22500.0	22500	5457000	130
A70		1		1	22500.0	22500	5479500	129
A160		6		1	22600.0	22600	5502100	128
A160		5		1	22600.0	22600	5524700	127
A160		4		1	22600.0	22600	5547300	126
A160		3		1	22600.0	22600	5569900	125
A160		2		1	22600.0	22600	5592500	124
A160		1		1	22600.0	22600	5615100	123

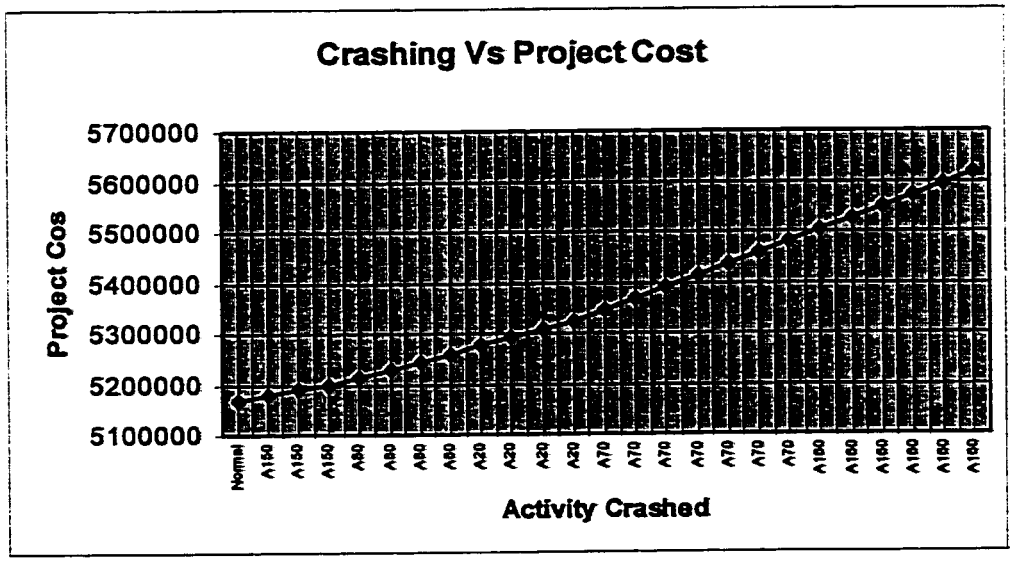

Figure 6.3 : Graph between Activities crashing and their respective Project cost

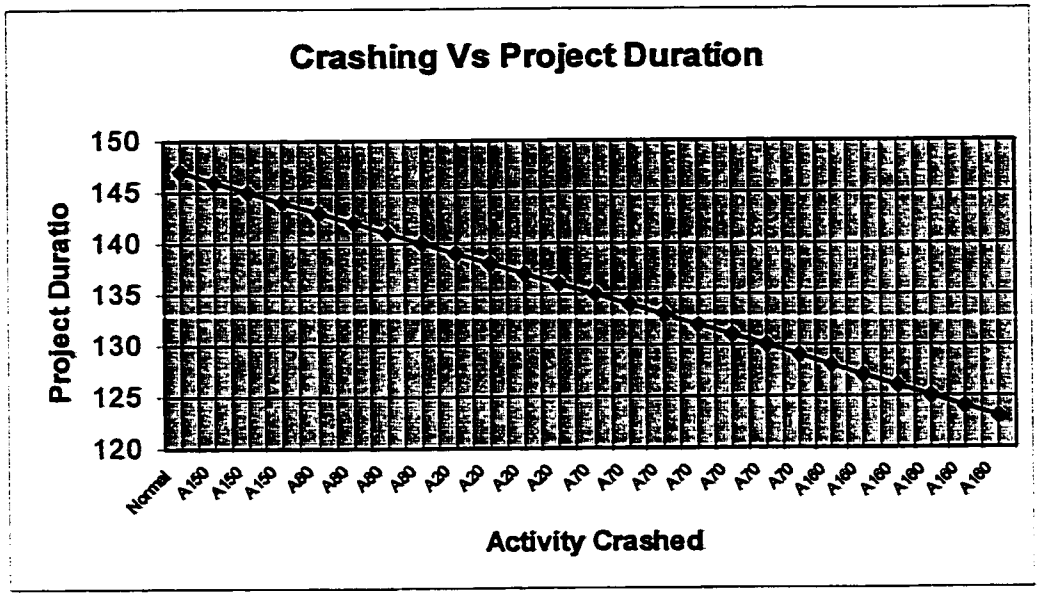

Figure 6.4 : Graph between Activities crashing and their respective Project duration

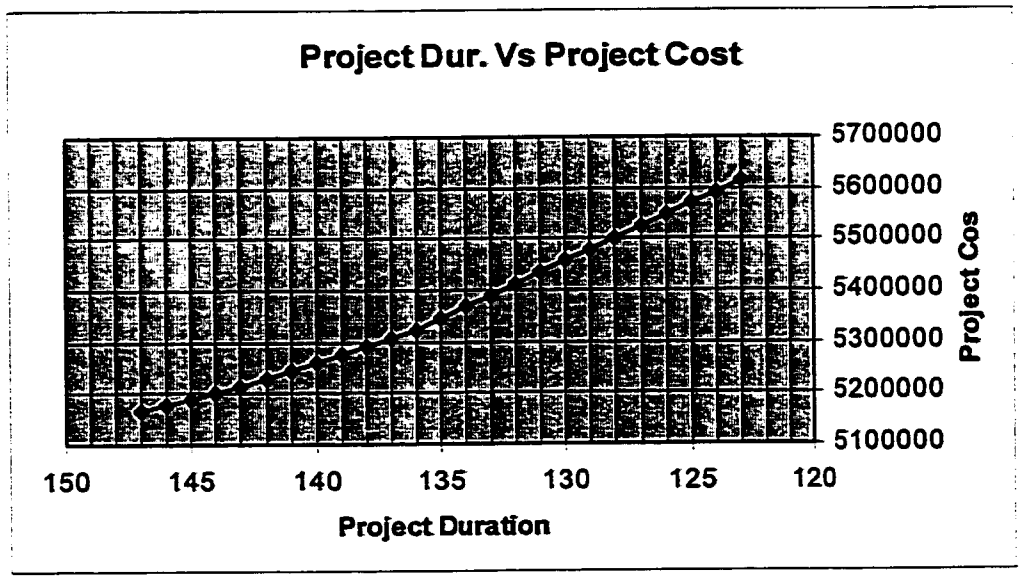

Figure 6.5 : Graph between Project Duration and their respective costs

6.5.2 Time-Cost Trade-off by STROBOSCOPE Simulation

Output data was received from all simulation runs regarding several aspects of activities and project. On activity level, results were average time of activity, average early start time, average late start time, average early finish time, average late finish time, average free float, average total float, percent criticality, average cost. On project side, averages project duration. Standard deviation of project duration, average project cost, standard deviation of project cost, and 95% confidence interval for project duration and project cost were gathered. Table 6.4 is the selective data collected from all simulation runs.

Table 6.4: Selective results from all simulation runs

Simulation Run Description	Average Project Duration	Std. Dev. of Project Duration	95% C.I. on Project D. Lower	95% C.I. on Project D. Upper	Average Project Cost	Std. Dev. of Project Cost	95% C.I. on Project C. Lower	95% C.I. on Project C. Upper
Normal	146.96	1.08	146.56	147.36	5164104	24211	5155063	5173145
A20 Crashed	143.03	1.15	142.60	143.45	5230359	25721	5220754	5239964
A30 Crashed	143.01	1.07	142.60	143.40	5255928	24562	5246756	5265099
A70 Crashed	136.05	1.09	135.64	136.45	5408896	26469	5399012	5418780
A80 Crashed	131.96	1.09	131.55	132.36	5472514	27860	5462111	5482917
A90 Crashed	132.13	1.08	131.72	132.53	5588064	28794	5577312	5598816
A130 Crashed	131.79	1.11	131.38	132.21	5625183	30496	5613795	5636570
A150 Crashed	129.13	1.10	128.73	129.54	5655833	33287	5643404	5668263
A160 Crashed	123.04	1.09	122.63	123.44	5788908	34757	5775930	5801886
A190 Crashed	123.02	1.13	122.60	123.45	5799653	34817	5786652	5812654
A200 Crashed	123.10	1.08	122.69	123.50	5820585	36146	5807088	5834082
A250 Crashed	122.98	1.09	122.57	123.38	5827017	35700	5813687	5840347
Selected Crashed	122.91	1.03	122.52	123.29	5616532	33802	5603910	5629154

It was noticed that, while crashing, several activities are not causing any change in over all project duration. Clearly, these activities are not critical for project duration. Figure 6.6 presents the results gathered for average project duration in terms of activities crashing. Average project duration, that was 146.96 days for normal schedule, reduced to 122.98 days with all activities reduced to their crashed duration. While 122.91 days project duration was achieved by crashing only the selected activities that were identified during previous runs.

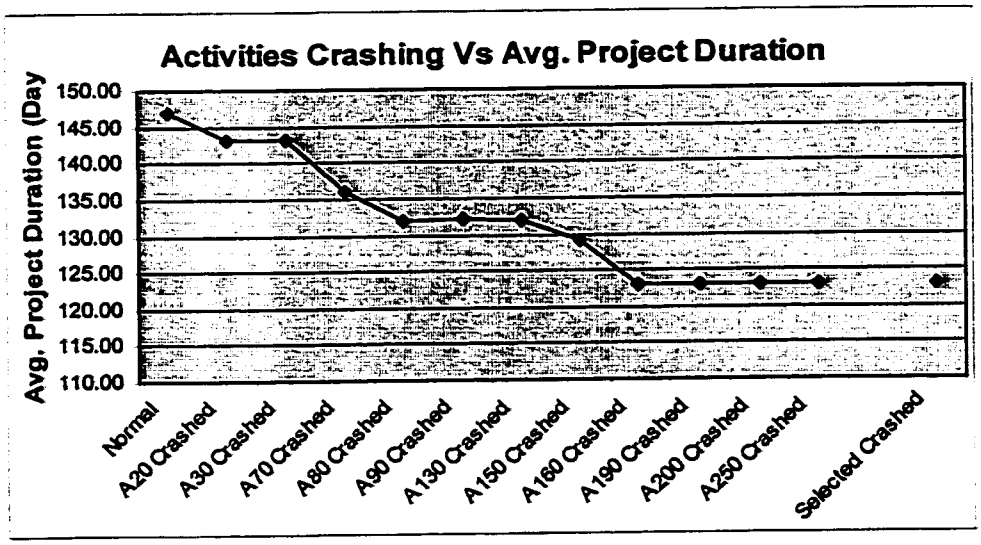

Figure 6.6: Results of Average project duration against reduction in activity duration

While some activities were causing decrement in overall project duration and some were not affecting it, average total cost of project continued to rise. This resulted in waste of resources in crashing those activities that were not significant for project duration change. These facts are evident from Figure 6.7.

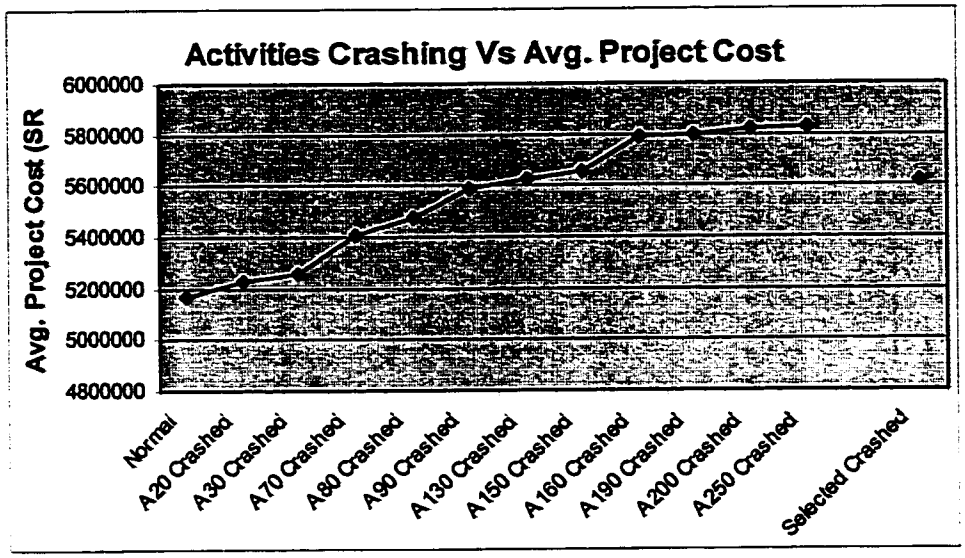

Figure 6.7: Results of Average project cost against reduction in activity duration

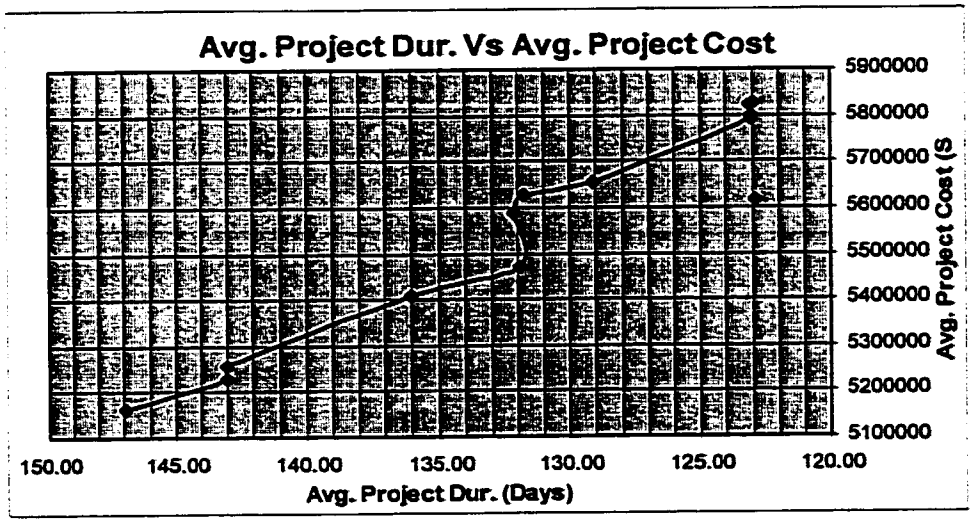

Figure 6.8: Results of Average project duration against Average project cost

To make this point clearer, results are presented in Figure 6.8. It represents average total project duration against average total project cost. At least in three regions, it is evident that cost is increasing but duration is unaffected.

Comparison of both approaches was made on two points i.e. project with normal duration and secondly with complete crashing of network. At both points, responses from conventional method came with in 95% confidence interval of responses from simulation. At Normal point, the total project duration from conventional method was +0.2 σ away from the average total project duration coming from simulation. While the total project cost from conventional method was +0.74 σ away from the average total project cost coming from simulation. At complete crash point, the total project duration from conventional method was +0.48 σ away from the average total project duration coming from simulation. While the total project cost from conventional method was -0.23 σ away from the average total project cost coming from simulation.

6.6 Conclusions

Analysis of results revealed several facts and observations could be rationalized in planning and decision making concerns. However, this was not an effort for integrating process level and project level simulation, but by breaking the total project into smaller activities, this tool can provide the basis for more reliable planning from management's perspective.

This work exhibited that STROBOSCOPE can be used as a planning tool, and unlike process simulation, considerably few simulation runs could give sufficient trends and options for decision making. Moreover, the CPM add-on is very useful for research and application as a probabilistic scheduling tool. If time is not a constraint and ample

computing power is available, (e.g. SMP or MPP machines) then some other approaches can also be utilized for trends that are more reliable and detailed information gathering. One such approach could be to crash each activity day-by-day rather than crashing it completely. This will certainly asks for high powered equipment as it will increase the amount of computing work required, many folds.

Additionally, it presented the fact that simulation gives trends and information for decision making and planning besides what-if testing facilities. However, the results t showed that there were not significant differences in project cost and duration while comparing conventional and stroboscope simulation, with in scope of the study. As the project duration and cost from conventional method came wit in 95% confidence interval of average total project duration and cost of simulation results, respectively. However, simulation did provide additional information that was unavailable with conventional methods e.g. standard deviation of activities, project cost and duration. Moreover, since distributions were used instead of single point estimate of activity duration, the results are more representative. In additional, confidence interval was available for the gathered results while conventional method did not provide it.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Final phase of any simulation modeling is finding out some meaningful results and based on these results, decisions have to be made. Interpretation of results plays very important role in decision making, therefore, simulation output and trends have to be read carefully and by someone with sufficient knowledge and expertise in the relevant area. Additional run option may be adopted at this stage if the need arises. Although, implementation of conclusions and decisions made based on results, is next step. The scope of this study remains limited to the presentation of results and recommendations.

Simulation runs can provide loads of output data, and in many cases, that can be difficult to interpret. Due to the STROBOSCOPE's flexibility of output reports, it is much easier to get only the most relevant or required results from a simulation run. Simulation run provides different aspects of variables e.g. average, total, standard deviation, range, and criticality for any activity or for the whole project. Moreover, it provides time series data that shows the trend of variable under consideration and provides a basis for forecasting. Additionally, sensitivity analysis can be performed to

observe the reactiveness of one variable to change in another variable or multiple variables.

The work illustrates STROBOSCOPE's power as a general-purpose simulation system. Complex and realistic problems such as the examples presented can be modeled, analyzed and optimized quite easily. In addition, it presented the fact that simulation can give trends and information for decision making and planning besides what-if testing facilities. It also exhibited that STROBOSCOPE can be used as a planning tool, and unlike process simulation, considerably few simulation runs could give sufficient trends and options for decision making. Moreover, the CPM add-on is very useful for research and application as a probabilistic scheduling tool.

In first part of the work, after analyzing the results obtained from using PERT method and STROBOSCOPE simulation language, several facts were revealed. Total duration of project were nearly same by PERT as average total duration by simulation. This depicts that PERT is a good approximation as long as total duration is the only criteria and multiple parallel paths with near equal duration are absent which eliminates chances of merge-event bias. Another fact noticed was that in most cases, simulation showed more activities as critical than of PERT method. In addition, it presented the fact that simulation gives additional information about activities that are critical or prone to be critical. This information cannot be provided using other methods e.g. PERT.

In second part of the work, The result shows that not all the variables affect the total duration and cost of the project with in the scope of work. From five variables, Ground Men crew came out to be especially affecting the cost and duration of project as by adding crew, total duration, and in turn cost, continues to drop. This seems to happen because of the requirement of ground men on several queues resource input. Project's vital statistics i.e. duration and cost, decreased when number of Tensioner increased to two, but showed no effect afterwards while increasing number of Tensioner. Other variables did not pay any significant role in changing the project's cost and duration. For further help in interpretation of the trends, combined graphs for various variables can be used as in Fig. 5.6.a and 5.6.b. . Although, it was not an attempt to optimize considering all variables simultaneously, rather individually on the basis of practicality, results of this approach can provide a foundation for near optimized decision making.

Third part of the work provided several facts and observations that could be rationalized in planning and decision-making concerns. However, this was not an effort for integrating process level and project level simulation, but by breaking the total project into activities, this tool can provide the basis for more reliable planning from management's perspective. Although, the results did not show significant differences in project cost and duration while comparing conventional and STROBOSCOPE simulation, but simulation did provide additional information that was unavailable with conventional methods. Moreover, since distributions were used instead of single point estimate of activity duration, the results are more reliable. In additional, 95% confidence

interval was available for the gathered results while conventional method did not provide it.

7.2 RECOMMENDATIONS

The study reveals that simulation has powerful analytical capabilities. Simulation studies require extensive data. Therefore, the construction industry should be informed about the nature and type of the data required for a simulation study. This study was an attempt at using stroboscope simulation in construction industry at large. While the study was successful in demonstrating potential, it also opened the need for additional work. The following recommendations are made for future research to further refine and extend the work presented and to increase the simulation in construction.

- Since several different statistical distribution options were tried while simulating schedules of linear projects, and not much different were found in trend. So, a different linear project can be modeled with the certain presence of merge-event bias to know the variation from conventional method.
- Simulation model for schedules of linear project can also be constructed the tool ProbSched for STROBOSCOPE, instead of writing the code. It will further ease the simulation modeling but certainly at a cost, as models are limited to the features available in ProbSched, though quite enough for most type of model development, is less flexible than full featured CPM-Add-on coding option.

- While simulating stringing of overhead transmission line conductors and overhead ground wires, model was developed using crew for Ground Men and Line Men instead of individuals as in general field practice. A further detailed model can be developed using individual approach to know the optimized crew sizes.
- Another model of the process can be developed for simulating multiple variables in combination or simultaneously, provided that enough resources are available for this practice i.e. high performance machine with capability of running the software, which is a 32-bit window based.
- Also in simulation of Time-Cost trade-off for the construction of flow lines, another model with a different approach can be constructed, if ample computing power is available. Two such approaches are described in sections 6.4.3 and 6.6.
- The models simulated in this research derived from reality but it ignored some factor such as scheduled maintenance activities, workers productivity, idle time, etc. These and other real-life elements can be incorporated into the model. As mentioned before, the models developed in this research are flexible and adaptable to future changes.
- A significant future research area is the development of Precedence network Add-on for STROBOSCOPE, as currently available CPM Add-on does not have the capability to define activities relationship other than Finish-to-Start, hence lacking flexibility which is needed for many construction operations.

APPENDICES

APPENDIX A : *STROBOSCOPE Source Codes for Project Example in Simulation of Linear Schedule*

CASE 1: STROBOSCOPE Source Code with Bell-Shaped Pert Distribution

```
VARIABLE nReplications 50;
SEED 911964;
STREAMS 30;
LOADADDON CpmAddon.dll;
/---------- Defining Activities and their Duration in terms of Pert
distribution
CPMACTIVITY LC1 sPert[0.5,1,1.5,1];
CPMACTIVITY EX1 sPert[1,4,7,2];
CPMACTIVITY ST1 sPert[1,2,3,3];
CPMACTIVITY LA1 sPert[1,5,9,4];
CPMACTIVITY TE1 sPert[1.5,2,2.5,5];
CPMACTIVITY BF1 sPert[0.5,1,1.5,6];

CPMACTIVITY LC2 sPert[0.5,1,1.5,7];
CPMACTIVITY EX2 sPert[1,3,5,8];
CPMACTIVITY ST2 sPert[1,3,5,9];
CPMACTIVITY LA2 sPert[2,6,10,10];
CPMACTIVITY TE2 sPert[1.5,2,2.5,11];
CPMACTIVITY BF2 sPert[0.5,1,1.5,12];

CPMACTIVITY LC3 sPert[0.5,1,1.5,13];
CPMACTIVITY EX3 sPert[1,4,7,14];
CPMACTIVITY ST3 sPert[1,2,3,15];
CPMACTIVITY LA3 sPert[1,5,9,16];
CPMACTIVITY TE3 sPert[1.5,2,2.5,17];
CPMACTIVITY BF3 sPert[0.5,1,1.5,18];

CPMACTIVITY LC4 sPert[0.5,1,1.5,19];
CPMACTIVITY EX4 sPert[2,6,10,20];
CPMACTIVITY ST4 sPert[2,4,6,21];
CPMACTIVITY LA4 sPert[2,6,10,22];
CPMACTIVITY TE4 sPert[1,2,3,23];
CPMACTIVITY BF4 sPert[2,4,6,24];

CPMACTIVITY LC5 sPert[0.5,1,1.5,25];
CPMACTIVITY EX5 sPert[1,3,5,26];
CPMACTIVITY ST5 sPert[1,3,5,27];
CPMACTIVITY LA5 sPert[2,6,10,28];
CPMACTIVITY TE5 sPert[1.5,2,2.5,29];
CPMACTIVITY BF5 sPert[0.5,1,1.5,30];

/--------- Precedence relationships for the First stage
PRECEDENCE LC1 EX1;
```

```
PRECEDENCE LC1 ST1;
PRECEDENCE LC1 LC2;

PRECEDENCE EX1 LA1;
PRECEDENCE EX1 EX2;

PRECEDENCE ST1 LA1;
PRECEDENCE ST1 ST2;

PRECEDENCE LA1 TE1;
PRECEDENCE LA1 LA2;

PRECEDENCE TE1 BF1;
PRECEDENCE TE1 TE2;

PRECEDENCE BF1 BF2;
/--------- Precedence relationships for the Second stage
PRECEDENCE LC2 EX2;
PRECEDENCE LC2 ST2;
PRECEDENCE LC2 LC3;

PRECEDENCE EX2 LA2;
PRECEDENCE EX2 EX3;

PRECEDENCE ST2 LA2;
PRECEDENCE ST2 ST3;

PRECEDENCE LA2 TE2;
PRECEDENCE LA2 LA3;

PRECEDENCE TE2 BF2;
PRECEDENCE TE2 TE3;

PRECEDENCE BF2 BF3;
/--------- Precedence relationships for the Third stage
PRECEDENCE LC3 EX3;
PRECEDENCE LC3 ST3;
PRECEDENCE LC3 LC4;

PRECEDENCE EX3 LA3;
PRECEDENCE EX3 EX4;

PRECEDENCE ST3 LA3;
PRECEDENCE ST3 ST4;

PRECEDENCE LA3 TE3;
PRECEDENCE LA3 LA4;

PRECEDENCE TE3 BF3;
PRECEDENCE TE3 TE4;

PRECEDENCE BF3 BF4;
/--------- Precedence relationships for the Fourth stage
```

```
PRECEDENCE LC4 EX4;
PRECEDENCE LC4 ST4;
PRECEDENCE LC4 LC5;

PRECEDENCE EX4 LA4;
PRECEDENCE EX4 EX5;

PRECEDENCE ST4 LA4;
PRECEDENCE ST4 ST5;

PRECEDENCE LA4 TE4;
PRECEDENCE LA4 LA5;

PRECEDENCE TE4 BF4;
PRECEDENCE TE4 TE5;

PRECEDENCE BF4 BF5;
/--------- Precedence relationships for the Fifth stage
PRECEDENCE LC5 EX5;
PRECEDENCE LC5 ST5;
PRECEDENCE EX5 LA5;
PRECEDENCE ST5 LA5;
PRECEDENCE LA5 TE5;
PRECEDENCE TE5 BF5;
/--------- Number of Replications and Reporting the Results
CPMREPLICATE nReplications;

PRINT StdOutput
"\n 95%% Confidence Interval on Project duration is : [%6.2f, %6.2f]"
'ProjectDur.AveVal-Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]'
'ProjectDur.AveVal+Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]';

REPORT;
```

CASE 2: STROBOSCOPE Source Code with Bell-Shaped Pert Distribution with Smaller Duration Ranges

```
VARIABLE nReplications 50;
SEED 911964;
STREAMS 30;
LOADADDON CpmAddon.dll;
/---------- Defining Activities and their Duration in terms of Pert
distribution
CPMACTIVITY LC1 sPert[1,2,3,1];
CPMACTIVITY EX1 sPert[4,5,6,2];
CPMACTIVITY ST1 sPert[2,3,4,3];
CPMACTIVITY LA1 sPert[5,6,7,4];
CPMACTIVITY TE1 sPert[2,3,4,5];
CPMACTIVITY BF1 sPert[1,2,3,6];
```

```
CPMACTIVITY LC2 sPert[1,2,3,7];
CPMACTIVITY EX2 sPert[3,4,5,8];
CPMACTIVITY ST2 sPert[3,4,5,9];
CPMACTIVITY LA2 sPert[6,7,8,10];
CPMACTIVITY TE2 sPert[2,3,4,11];
CPMACTIVITY BF2 sPert[1,2,3,12];

CPMACTIVITY LC3 sPert[1,2,3,13];
CPMACTIVITY EX3 sPert[4,5,6,14];
CPMACTIVITY ST3 sPert[2,3,4,15];
CPMACTIVITY LA3 sPert[5,6,7,16];
CPMACTIVITY TE3 sPert[2,3,4,17];
CPMACTIVITY BF3 sPert[1,2,3,18];

CPMACTIVITY LC4 sPert[1,2,3,19];
CPMACTIVITY EX4 sPert[6,7,8,20];
CPMACTIVITY ST4 sPert[4,5,6,21];
CPMACTIVITY LA4 sPert[6,7,8,22];
CPMACTIVITY TE4 sPert[2,3,4,23];
CPMACTIVITY BF4 sPert[4,5,6,24];

CPMACTIVITY LC5 sPert[1,2,3,25];
CPMACTIVITY EX5 sPert[3,4,5,26];
CPMACTIVITY ST5 sPert[3,4,5,27];
CPMACTIVITY LA5 sPert[6,7,8,28];
CPMACTIVITY TE5 sPert[2,3,4,29];
CPMACTIVITY BF5 sPert[1,2,3,30];

/--------- Precedence relationships for the First stage
PRECEDENCE LC1 EX1;
PRECEDENCE LC1 ST1;
PRECEDENCE LC1 LC2;

PRECEDENCE EX1 LA1;
PRECEDENCE EX1 EX2;

PRECEDENCE ST1 LA1;
PRECEDENCE ST1 ST2;

PRECEDENCE LA1 TE1;
PRECEDENCE LA1 LA2;

PRECEDENCE TE1 BF1;
PRECEDENCE TE1 TE2;

PRECEDENCE BF1 BF2;
/--------- Precedence relationships for the Second stage
PRECEDENCE LC2 EX2;
PRECEDENCE LC2 ST2;
PRECEDENCE LC2 LC3;

PRECEDENCE EX2 LA2;
PRECEDENCE EX2 EX3;
```

```
PRECEDENCE ST2 LA2;
PRECEDENCE ST2 ST3;

PRECEDENCE LA2 TE2;
PRECEDENCE LA2 LA3;

PRECEDENCE TE2 BF2;
PRECEDENCE TE2 TE3;

PRECEDENCE BF2 BF3;
/--------- Precedence relationships for the Third stage
PRECEDENCE LC3 EX3;
PRECEDENCE LC3 ST3;
PRECEDENCE LC3 LC4;

PRECEDENCE EX3 LA3;
PRECEDENCE EX3 EX4;

PRECEDENCE ST3 LA3;
PRECEDENCE ST3 ST4;

PRECEDENCE LA3 TE3;
PRECEDENCE LA3 LA4;

PRECEDENCE TE3 BF3;
PRECEDENCE TE3 TE4;

PRECEDENCE BF3 BF4;
/--------- Precedence relationships for the Fourth stage
PRECEDENCE LC4 EX4;
PRECEDENCE LC4 ST4;
PRECEDENCE LC4 LC5;

PRECEDENCE EX4 LA4;
PRECEDENCE EX4 EX5;

PRECEDENCE ST4 LA4;
PRECEDENCE ST4 ST5;

PRECEDENCE LA4 TE4;
PRECEDENCE LA4 LA5;

PRECEDENCE TE4 BF4;
PRECEDENCE TE4 TE5;

PRECEDENCE BF4 BF5;
/--------- Precedence relationships for the Fifth stage
PRECEDENCE LC5 EX5;
PRECEDENCE LC5 ST5;
PRECEDENCE EX5 LA5;
PRECEDENCE ST5 LA5;
PRECEDENCE LA5 TE5;
```

```
PRECEDENCE TE5 BF5;
/--------- Number of Replications and Reporting the Results
CPMREPLICATE nReplications;

PRINT StdOutput
"\n 95%% Confidence Interval on Project duration is : [%6.2f, %6.2f]"
'ProjectDur.AveVal-Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]'
'ProjectDur.AveVal+Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]';

REPORT;
```

CASE 3: STROBOSCOPE Source Code with Bell-Shaped Normal Distribution with Smaller Duration Ranges

```
VARIABLE nReplications 50;
SEED 911964;
STREAMS 30;
LOADADDON CpmAddon.dll;
/---------- Defining Activities and their Duration in terms of Pert
distribution
CPMACTIVITY LC1 sNormal[2,0.33,1];
CPMACTIVITY EX1 sNormal[5,0.33,2];
CPMACTIVITY ST1 sNormal[3,0.33,3];
CPMACTIVITY LA1 sNormal[6,0.33,4];
CPMACTIVITY TE1 sNormal[3,0.33,5];
CPMACTIVITY BF1 sNormal[2,0.33,6];

CPMACTIVITY LC2 sNormal[2,0.33,7];
CPMACTIVITY EX2 sNormal[4,0.33,8];
CPMACTIVITY ST2 sNormal[4,0.33,9];
CPMACTIVITY LA2 sNormal[7,0.33,10];
CPMACTIVITY TE2 sNormal[3,0.33,11];
CPMACTIVITY BF2 sNormal[2,0.33,12];

CPMACTIVITY LC3 sNormal[2,0.33,13];
CPMACTIVITY EX3 sNormal[5,0.33,14];
CPMACTIVITY ST3 sNormal[3,0.33,15];
CPMACTIVITY LA3 sNormal[6,0.33,16];
CPMACTIVITY TE3 sNormal[3,0.33,17];
CPMACTIVITY BF3 sNormal[2,0.33,18];

CPMACTIVITY LC4 sNormal[2,0.33,19];
CPMACTIVITY EX4 sNormal[7,0.33,20];
CPMACTIVITY ST4 sNormal[5,0.33,21];
CPMACTIVITY LA4 sNormal[7,0.33,22];
CPMACTIVITY TE4 sNormal[3,0.33,23];
CPMACTIVITY BF4 sNormal[5,0.33,24];

CPMACTIVITY LC5 sNormal[2,0.33,25];
CPMACTIVITY EX5 sNormal[4,0.33,26];
CPMACTIVITY ST5 sNormal[4,0.33,27];
```

```
CPMACTIVITY LA5 sNormal[7,0.33,28];
CPMACTIVITY TE5 sNormal[3,0.33,29];
CPMACTIVITY BF5 sNormal[2,0.33,30];

/--------- Precedence relationships for the First stage
PRECEDENCE LC1 EX1;
PRECEDENCE LC1 ST1;
PRECEDENCE LC1 LC2;

PRECEDENCE EX1 LA1;
PRECEDENCE EX1 EX2;

PRECEDENCE ST1 LA1;
PRECEDENCE ST1 ST2;

PRECEDENCE LA1 TE1;
PRECEDENCE LA1 LA2;

PRECEDENCE TE1 BF1;
PRECEDENCE TE1 TE2;

PRECEDENCE BF1 BF2;
/--------- Precedence relationships for the Second stage
PRECEDENCE LC2 EX2;
PRECEDENCE LC2 ST2;
PRECEDENCE LC2 LC3;

PRECEDENCE EX2 LA2;
PRECEDENCE EX2 EX3;

PRECEDENCE ST2 LA2;
PRECEDENCE ST2 ST3;

PRECEDENCE LA2 TE2;
PRECEDENCE LA2 LA3;

PRECEDENCE TE2 BF2;
PRECEDENCE TE2 TE3;

PRECEDENCE BF2 BF3;
/--------- Precedence relationships for the Third stage
PRECEDENCE LC3 EX3;
PRECEDENCE LC3 ST3;
PRECEDENCE LC3 LC4;

PRECEDENCE EX3 LA3;
PRECEDENCE EX3 EX4;

PRECEDENCE ST3 LA3;
PRECEDENCE ST3 ST4;

PRECEDENCE LA3 TE3;
PRECEDENCE LA3 LA4;
```

```
PRECEDENCE TE3 BF3;
PRECEDENCE TE3 TE4;

PRECEDENCE BF3 BF4;
/--------- Precedence relationships for the Fourth stage
PRECEDENCE LC4 EX4;
PRECEDENCE LC4 ST4;
PRECEDENCE LC4 LC5;

PRECEDENCE EX4 LA4;
PRECEDENCE EX4 EX5;

PRECEDENCE ST4 LA4;
PRECEDENCE ST4 ST5;

PRECEDENCE LA4 TE4;
PRECEDENCE LA4 LA5;

PRECEDENCE TE4 BF4;
PRECEDENCE TE4 TE5;

PRECEDENCE BF4 BF5;
/--------- Precedence relationships for the Fifth stage
PRECEDENCE LC5 EX5;
PRECEDENCE LC5 ST5;
PRECEDENCE EX5 LA5;
PRECEDENCE ST5 LA5;
PRECEDENCE LA5 TE5;
PRECEDENCE TE5 BF5;
/--------- Number of Replications and Reporting the Results
CPMREPLICATE nReplications;

PRINT StdOutput
"\n 95%% Confidence Interval on Project duration is : [%6.2f, %6.2f]"
'ProjectDur.AveVal-Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]'
'ProjectDur.AveVal+Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]';

REPORT;
```

CASE 4: STROBOSCOPE Source Code with Skewed-to-Right Pert Distribution

```
VARIABLE nReplications 50;
SEED 911964;
STREAMS 30;
LOADADDON CpmAddon.dll;
/---------- Defining Activities and their Duration in terms of Pert
distribution
CPMACTIVITY LC1 sPert[1,1.5,2.5,1];
CPMACTIVITY EX1 sPert[1,4,8,2];
```

```
CPMACTIVITY ST1 sPert[1,2,4,3];
CPMACTIVITY LA1 sPert[1,5,10,4];
CPMACTIVITY TE1 sPert[2,2.5,3.5,5];
CPMACTIVITY BF1 sPert[1,1.5,2.5,6];

CPMACTIVITY LC2 sPert[1,1.5,2.5,7];
CPMACTIVITY EX2 sPert[1,3,6,8];
CPMACTIVITY ST2 sPert[1,3,6,9];
CPMACTIVITY LA2 sPert[2,6,11,10];
CPMACTIVITY TE2 sPert[2,2.5,3.5,11];
CPMACTIVITY BF2 sPert[1,1.5,2.5,12];

CPMACTIVITY LC3 sPert[1,1.5,2.5,13];
CPMACTIVITY EX3 sPert[1,4,8,14];
CPMACTIVITY ST3 sPert[1,2,4,15];
CPMACTIVITY LA3 sPert[1,5,10,16];
CPMACTIVITY TE3 sPert[2,2.5,3.5,17];
CPMACTIVITY BF3 sPert[1,1.5,2.5,18];

CPMACTIVITY LC4 sPert[1,1.5,2.5,19];
CPMACTIVITY EX4 sPert[2,6,11,20];
CPMACTIVITY ST4 sPert[2,4,7,21];
CPMACTIVITY LA4 sPert[2,6,11,22];
CPMACTIVITY TE4 sPert[1,2,4,23];
CPMACTIVITY BF4 sPert[2,4,7,24];

CPMACTIVITY LC5 sPert[1,1.5,2.5,25];
CPMACTIVITY EX5 sPert[1,3,6,26];
CPMACTIVITY ST5 sPert[1,3,6,27];
CPMACTIVITY LA5 sPert[2,6,11,28];
CPMACTIVITY TE5 sPert[2,2.5,3.5,29];
CPMACTIVITY BF5 sPert[1,1.5,2.5,30];

/--------- Precedence relationships for the First stage
PRECEDENCE LC1 EX1;
PRECEDENCE LC1 ST1;
PRECEDENCE LC1 LC2;

PRECEDENCE EX1 LA1;
PRECEDENCE EX1 EX2;

PRECEDENCE ST1 LA1;
PRECEDENCE ST1 ST2;

PRECEDENCE LA1 TE1;
PRECEDENCE LA1 LA2;

PRECEDENCE TE1 BF1;
PRECEDENCE TE1 TE2;

PRECEDENCE BF1 BF2;
/--------- Precedence relationships for the Second stage
PRECEDENCE LC2 EX2;
```

```
PRECEDENCE LC2 ST2;
PRECEDENCE LC2 LC3;

PRECEDENCE EX2 LA2;
PRECEDENCE EX2 EX3;

PRECEDENCE ST2 LA2;
PRECEDENCE ST2 ST3;

PRECEDENCE LA2 TE2;
PRECEDENCE LA2 LA3;

PRECEDENCE TE2 BF2;
PRECEDENCE TE2 TE3;

PRECEDENCE BF2 BF3;

/--------- Precedence relationships for the Third stage
PRECEDENCE LC3 EX3;
PRECEDENCE LC3 ST3;
PRECEDENCE LC3 LC4;

PRECEDENCE EX3 LA3;
PRECEDENCE EX3 EX4;

PRECEDENCE ST3 LA3;
PRECEDENCE ST3 ST4;

PRECEDENCE LA3 TE3;
PRECEDENCE LA3 LA4;

PRECEDENCE TE3 BF3;
PRECEDENCE TE3 TE4;

PRECEDENCE BF3 BF4;
/--------- Precedence relationships for the Fourth stage
PRECEDENCE LC4 EX4;
PRECEDENCE LC4 ST4;
PRECEDENCE LC4 LC5;

PRECEDENCE EX4 LA4;
PRECEDENCE EX4 EX5;

PRECEDENCE ST4 LA4;
PRECEDENCE ST4 ST5;

PRECEDENCE LA4 TE4;
PRECEDENCE LA4 LA5;

PRECEDENCE TE4 BF4;
PRECEDENCE TE4 TE5;

PRECEDENCE BF4 BF5;
```

```
/--------- Precedence relationships for the Fifth stage
PRECEDENCE LC5 EX5;
PRECEDENCE LC5 ST5;
PRECEDENCE EX5 LA5;
PRECEDENCE ST5 LA5;
PRECEDENCE LA5 TE5;
PRECEDENCE TE5 BF5;
/--------- Number of Replications and Reporting the Results
CPMREPLICATE nReplications;

PRINT StdOutput
"\n 95%% Confidence Interval on Project duration is : [%6.2f, %6.2f]"
'ProjectDur.AveVal-Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]'
'ProjectDur.AveVal+Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]';

REPORT;
```

CASE 5: STROBOSCOPE Source Code with Skewed-to-Left Pert Distribution

```
VARIABLE nReplications 50;
SEED 911964;
STREAMS 30;
LOADADDON CpmAddon.dll;
/---------- Defining Activities and their Duration in terms of Pert
distribution
CPMACTIVITY LC1 sPert[1,1.5,2,1];
CPMACTIVITY EX1 sPert[1,4,6,2];
CPMACTIVITY ST1 sPert[1,2,3,3];
CPMACTIVITY LA1 sPert[1,5,8,4];
CPMACTIVITY TE1 sPert[2,2.5,3,5];
CPMACTIVITY BF1 sPert[1,1.5,2,6];

CPMACTIVITY LC2 sPert[1,1.5,2,7];
CPMACTIVITY EX2 sPert[1,3,4,8];
CPMACTIVITY ST2 sPert[1,3,4,9];
CPMACTIVITY LA2 sPert[2,6,9,10];
CPMACTIVITY TE2 sPert[2,2.5,3,11];
CPMACTIVITY BF2 sPert[1,1.5,2,12];

CPMACTIVITY LC3 sPert[1,1.5,2,13];
CPMACTIVITY EX3 sPert[1,4,6,14];
CPMACTIVITY ST3 sPert[1,2,3,15];
CPMACTIVITY LA3 sPert[1,5,8,16];
CPMACTIVITY TE3 sPert[2,2.5,3,17];
CPMACTIVITY BF3 sPert[1,1.5,2,18];

CPMACTIVITY LC4 sPert[1,1.5,2,19];
```

```
CPMACTIVITY EX4 sPert[2,6,9,20];
CPMACTIVITY ST4 sPert[2,4,5,21];
CPMACTIVITY LA4 sPert[2,6,9,22];
CPMACTIVITY TE4 sPert[1,2,3,23];
CPMACTIVITY BF4 sPert[2,4,5,24];

CPMACTIVITY LC5 sPert[1,1.5,2,25];
CPMACTIVITY EX5 sPert[1,3,4,26];
CPMACTIVITY ST5 sPert[1,3,4,27];
CPMACTIVITY LA5 sPert[2,6,9,28];
CPMACTIVITY TE5 sPert[2,2.5,3,29];
CPMACTIVITY BF5 sPert[1,1.5,2,30];

/--------- Precedence relationships for the First stage
PRECEDENCE LC1 EX1;
PRECEDENCE LC1 ST1;
PRECEDENCE LC1 LC2;

PRECEDENCE EX1 LA1;
PRECEDENCE EX1 EX2;

PRECEDENCE ST1 LA1;
PRECEDENCE ST1 ST2;

PRECEDENCE LA1 TE1;
PRECEDENCE LA1 LA2;

PRECEDENCE TE1 BF1;
PRECEDENCE TE1 TE2;

PRECEDENCE BF1 BF2;
/--------- Precedence relationships for the Second stage
PRECEDENCE LC2 EX2;
PRECEDENCE LC2 ST2;
PRECEDENCE LC2 LC3;

PRECEDENCE EX2 LA2;
PRECEDENCE EX2 EX3;

PRECEDENCE ST2 LA2;
PRECEDENCE ST2 ST3;

PRECEDENCE LA2 TE2;
PRECEDENCE LA2 LA3;

PRECEDENCE TE2 BF2;
PRECEDENCE TE2 TE3;

PRECEDENCE BF2 BF3;
/--------- Precedence relationships for the Third stage
PRECEDENCE LC3 EX3;
PRECEDENCE LC3 ST3;
PRECEDENCE LC3 LC4;
```

```
PRECEDENCE EX3 LA3;
PRECEDENCE EX3 EX4;

PRECEDENCE ST3 LA3;
PRECEDENCE ST3 ST4;

PRECEDENCE LA3 TE3;
PRECEDENCE LA3 LA4;

PRECEDENCE TE3 BF3;
PRECEDENCE TE3 TE4;

PRECEDENCE BF3 BF4;
/--------- Precedence relationships for the Fourth stage
PRECEDENCE LC4 EX4;
PRECEDENCE LC4 ST4;
PRECEDENCE LC4 LC5;

PRECEDENCE EX4 LA4;
PRECEDENCE EX4 EX5;

PRECEDENCE ST4 LA4;
PRECEDENCE ST4 ST5;

PRECEDENCE LA4 TE4;
PRECEDENCE LA4 LA5;

PRECEDENCE TE4 BF4;
PRECEDENCE TE4 TE5;

PRECEDENCE BF4 BF5;
/--------- Precedence relationships for the Fifth stage
PRECEDENCE LC5 EX5;
PRECEDENCE LC5 ST5;
PRECEDENCE EX5 LA5;
PRECEDENCE ST5 LA5;
PRECEDENCE LA5 TE5;
PRECEDENCE TE5 BF5;
/--------- Number of Replications and Reporting the Results
CPMREPLICATE nReplications;

PRINT StdOutput
"\n 95%% Confidence Interval on Project duration is : [%6.2f, %6.2f]"
'ProjectDur.AveVal-Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]'
'ProjectDur.AveVal+Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]';

REPORT;
```

APPENDIX B : *STROBOSCOPE Source Code for Project Example in Simulation of Stringing of Overhead Transmission Line Conductors and Overhead Ground Wires*

```
/*******************************************************************
/* Stroboscope source file generated from Visio drawing
/*******************************************************************
/ The purpose of this source code is to simulate a Stroboscope Model
/ for Stringing of overhead transmission line conductors and overhead
/ ground wires. The schematic diagram of the Stroboscope model is shown
/ in Figure 5.A. For explanation of the model, refer to the Figure 5.A
/ in addition to explanatory provided within this source code file.

/ ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
/ Stringing of overhead transmission line conductors

/ OBJECTIVE:
/ The objective of this example is to estimate the time required to
/ construct  a certain length of overhead power line
/(see illustrative drawing) and to find out the cost associated with
it.

/ Variables:
/ The variables used in the example project are as follows:
/1-   Length of the conductor
/2-   Number of take up reels


/ Elements need to do the work

/1-   Workmen
/1.1- Supervisor (See illustrative drawing mark W1)
/1.2- Ground men crews (See illustrative drawing mark W2)
/1.3- Linemen crews (See illustrative drawing mark W3)
/1.4- Pilot line winder / Conductor tensioner operator (See
      illustrative drawing mark W4)

/2-   Equipment
/2.1- Pilot line winder (See illustrative drawing mark E1)
/2.2- Conductor tensioner (See illustrative drawing mark E2)
/2.3- Tractor (See illustrative drawing mark E3)
/2.4- Take up reel stand  (See illustrative drawing mark E4)

/3-   Material
/3.1- Pilot line (See illustrative drawing mark M1)
/3.2- Conductor (See illustrative drawing mark M2)

/ First Stage
/1-   Pilot line winder operator will unwind the pilot line (W4+M1+E1).
```

```
/2-   Ground men will take the pilot line to tower (W2+M1).
/3-   Linemen will take the pilot line up to tower (W3+M1+W2).
/4-   Pilot line will be passed over the tower trough the traveler to
      other side (M1+W3).

/ Second Stage
/1-   After the pilot line pass over the steel tower is goes to ground
      and wait to be connected by ground men to a tractor (W2÷E3+M1).
/2-   Tractor travels 300m to the next steel tower (E3+M1).
/3-   Tractor wait in a Q to be disconnected from the pilot line
(E3+M1).
/4-   Groundmen disconnects pilot line from tractor (W2+M1+E3).
/5-   Tractor reposition itself and wait in a Q to be connected to
      pilot line to span to next steel tower (E3).
/6-   The next step is to check if the required conductor length has
      been reached or not. if it reached then the process of pulling
      the conductor over the steel towers will starts. If the length
      has not reached yet the process will go back to START stage.

/ Final Stage
/1-   When the pilot line reaches the last steel tower it connected to
      the conductor by the help of Groundmen (W2+M2+M1+E1+E2).
/2-   Pulling back the pilot line to it's winder in the starting side.
/3-   Since conductor is connected to the pilot line it will reach the
      starting side as soon as the pilot line   is completely winded.
/4-   The conductor is new over the steel towers.

/*********************************************************************
/* General section for problem parameters

/ -------- GLOBAL VARIABLES

/Time parameters for all resources will be assumed to be discrete. Time
will be in minutes and seconds.

SAVEVALUE   Replications*     10; / variable to define that how many
                                    times the model will run

VARIABLE ConductorLength 5000;       / in meters
VARIABLE NoOfGroundmenCrew 1;        / No. of crews
VARIABLE NoOfTensioner 1;      / conductor Tensioner machine, in numbers
VARIABLE LinemenCrew 1;        / No. of crews, W3
VARIABLE PilotLineWinder 1;    / in numbers, E1
VARIABLE LinemenPerCrew 6;     / Men per crew
VARIABLE GroundmenPerCrew 4;   / Men per crew
VARIABLE Tractor 1;            / No. of tractors, E3
VARIABLE Supervisor 1;         / No. of supervisor, W1
VARIABLE DecisionFlag 100;     / variable that defines how many times
                                 pilot line cycle can happen
VARIABLE Conductor ConductorLength; / variable to measure the end of
                               process
VARIABLE WinderOp 1;           / No of winder operator, W4
```

```
/ -------- COST VARIABLES
/ Cost for the rental and operation of each resource per hour
VARIABLE PilotLineWinderCost 250;   / SR/hr
VARIABLE TractorCost 250;           / SR/hr
VARIABLE ConductorTensionerCost 250; / SR/hr


/ -------- DURATION VARIABLES
/ Duration of each process interms of Pert distribution, in minutes
VARIABLE TimeToTower Pert[16,20,24];            /min
VARIABLE TimeThroughTravler Pert[3,5,7];        /min
VARIABLE TimeToTractor Pert[3,5,7];             /min
VARIABLE TimeTractorTravel Pert[8,10,12];       /min
VARIABLE TimeOutTractor Pert[4,5,6];            /min
VARIABLE TimeTractorReposition Pert[4,5,6];     /min
VARIABLE TimeConductorAnchor Pert[12,15,18];    /min
VARIABLE TravelOverTower Pert[75,85,95];        /min
VARIABLE TimePilotToCond Pert[13,15,17];        /min


/ -------- VARIABLES TO AID COMPUTATIONS
/ Vriables defined to make calulations simpler or to aid or to get the
results of desired aspect of the process
VARIABLE TotalHourCost
         'PilotLineWinderCost+TractorCost+ConductorTensionerCost';/
         SR/hr
VARIABLE TotalTime 'SimTime/60';
VARIABLE TotalCost 'TotalTime*TotalHourCost';   /SR

COLLECTOR TimeStats*;
COLLECTOR TCostStats*;
/*********************************************************************
/* Definition of resource types

GENTYPE          ConductorG;       / CO, Conductor (M2)
GENTYPE          GM;               / GM, GroundMen crew (W2)
GENTYPE          LM;               / LM, LineMen crew (W3)
GENTYPE          OrderG;           / OR, order by supervisor to go
GENTYPE          PilotLineG;       / PI, Pilot line (M1)
GENTYPE          SupervisorG;      / SU, Supervisor (W1)
GENTYPE          Tensioner;        / TE, Conductor tensioner (E2)
GENTYPE          TractorG;          TR, Tractor (E3)
GENTYPE          Winder;           / WI, Pilot line winder (E1)
GENTYPE          WO;               / WO, Winder operator (W4)

/*********************************************************************
/* Definition of network nodes

QUEUE GroundMenQ GM;            / Queue for resource GroundMenCrew
QUEUE LinemenQ LM;              / Queue for resource LineMen Crew
QUEUE WinderOperatorQ WO;       / Queue for resource Winder operator
QUEUE PilotLineWindrQ Winder;   / Queue for resource Pilot line winder
```

```
COMBI PilotToTower;            / Combi activity for taking the pilot
                               line to tower
QUEUE PilotLineGrndQ PilotLineG;    / Queue for resource Pilot line at
                                    ground
COMBI PilotToTractor;          / Combi activity for hooking the pilot
                               line to tractor
NORMAL Travel;            / Normal activity for tractor to travel 300m
QUEUE TractorWaiting TractorG;      / Queue for resource Tractor
                                    waiting to unhook
COMBI PilotOutTractor;         / Combi activity to take off pilot line
                               from tractor
QUEUE SupervisorQ SupervisorG;      / Queue for resource Supervisor
COMBI OrderC;                  / Combi activity for placing the order to
                               go by supervisor
NORMAL TractorPosition;        / Normal activity for tractor reposition
QUEUE TractorQ TractorG;       / Queue for resource Tractor
FORK  Decision OrderG;         / Fork for making the decision for end of
                               conductor length
NORMAL ConectToCondc;          / Normal activity for connecting the
                               pilot line to conductor
QUEUE ConductorQ ConductorG;   / Queue for resource Conductor
QUEUE NextPilotSegmnt OrderG;  / Queue for resource pilot line for next
                                     segment
COMBI PilotToConductr;         / Combi activity for hooking the pilot
                               line to conductor
COMBI StartPulingCond;   / Combi activity for start pulling the
                               conductor
COMBI Anchor;             / Combi activity to anchor the conductor
QUEUE AnchorQ Tensioner;       / Queue for resource anchoring conductor
QUEUE TensionerQ Tensioner;    / Queue for resource Tensioner
QUEUE PullBack Tensioner;      / Queue for resource Tensioner ready to
                               pullback

/*********************************************************************
/* Definition of network Links

LINK        GP1 GroundMenQ PilotToTower;  / GroundMen crew takes the
                                          pilot line from winder to
                                          tower
LINK        GP2 PilotToTower GroundMenQ;  / GroundMen crew after
                                          handling the pilot line to
                                          LineMen crew goes to the
                                          other side of the tower to
                                          connect the pilot line to
                                          tractor
LINK        PT1 PilotLineGrndQ PilotToTractor;
LINK        TD1 PilotToTractor Travel TractorG; / After connecting the
                                                pilot line to tractor
                                                it travels 300m to next
                                                steel tower
LINK        TD2 Travel TractorWaiting;
```

```
LINK        TD3 TractorWaiting PilotOutTractor; / Tractor waits to be
                                    disconnected from the pilot
                                    line by GroundMen crew
LINK        TD4 GroundMenQ PilotOutTractor;
LINK        TD5 PilotOutTractor GroundMenQ;
LINK        TD6 PilotOutTractor TractorPosition TractorG;   / After
                                          tractor disconnected,
                                          it repositions itself
                                          to pull the next
                                          segment of pilot line
LINK        TD7 TractorPosition TractorQ;  / Tractor returns to the
                                    Queue
LINK        TD8 PilotOutTractor SupervisorQ;    / Supervisor checks for
                                    the completion of the stage
LINK        TA1 SupervisorQ OrderC; / Supervisor gives the command to
                                  connect the pilot line to
                                  conductor and to pull it back if
                                  the required spans have been
                                  achieved
LINK        TA11 OrderC Decision;
LINK        TA2 Decision NextPilotSegmnt;
LINK        TA3 NextPilotSegmnt PilotToTower;
LINK        TA4 Decision ConectToCondc;
LINK        PC2 GroundMenQ PilotToConductr;
LINK        PC3 PilotToConductr GroundMenQ;
LINK        PC9 StartPulingCond PilotLineWindrQ;
LINK        PC8 PilotLineWindrQ StartPulingCond;

LINK        LP1 LinemenQ PilotToTower;     / LineMen crew takes the
                                    pilot line from GroundMen
                                    crew and goes up to the steel
                                    tower to pass the pilot line
                                    through the traveler
LINK        LP2 PilotToTower LinemenQ;     / LineMen crew goes to the
                                    next steel tower to be ready
                                    for the next pass
LINK        GT1 GroundMenQ PilotToTractor; / GroundMen crew connects
                                     the pilot line to tractor
LINK        GT2 PilotToTractor GroundMenQ; / and goes to the next tower

LINK        PC1 ConductorQ PilotToConductr;
LINK        AC1 StartPulingCond AnchorQ;  / Anchoring of the conductor
LINK        AC2 AnchorQ Anchor;           / If three phases of the
                                    conductor are complete then
                                    stop the process
LINK        AC3 Anchor TensionerQ;
LINK        PC4 PilotToConductr PullBack;
LINK        PC6 PullBack StartPulingCond;
LINK        OP1 WinderOperatorQ PilotToTower;    / Winder operator
                                    starts unwinding the pilot
                                    line by starting the pilot
                                    line
```

```
LINK        OP2 PilotToTower WinderOperatorQ;   / Winder operator goes
                                        back after completing the
                                        unwinding
LINK        TT1 TractorQ PilotToTractor;
LINK        TT2 PilotToTractor TractorQ;
LINK        PC5 TensionerQ PilotToConductr;
LINK        WP1 PilotToTower PilotLineWindrQ;    / Pilot line moves
                                        from winder by winder
                                        operator and groundmen crew
                                        takes it to steel tower
LINK        WP2 PilotLineWindrQ PilotToTower;  / Winder operator gets
                                           ready for the next
                                           pass
LINK        PG1 PilotToTower PilotLineGrndQ;    / Pilot line connects
                                        to the tractor after it
                                        passed over the steel tower
LINK        TA5 ConectToCondc ConductorQ;

DISPLAY
"                                                                    ";
DISPLAY "              Selected Results of Experiment of " ;
DISPLAY
"                                                                    ";
DISPLAY "Run#     Total Hourly Cost Total Duration    Total Cost ";
DISPLAY
"                                                                    ";

/*******************************************************************
/* Definition of global variables and programing objects

COLLECTOR PilotLineQ;    / this variable is to know if the pilot line is
                         finished and reached the required conductor
                         length
COLLECTOR AnchorCount;   / this variable is to know if the three phases
                         of the conductor anchored
/COLLECTOR TotalTime*;   / this variable is to collect the total time
                         spent for the complete project
/COLLECTOR TotalCost*;   / this variable is to find out the total cost
                         requirement associated with the completion of
                         the project
WHILE Replications;

/*******************************************************************
/* Startup of PilotToTower

DURATION          PilotToTower 'TimeToTower+TimeThroughTravler';

/*******************************************************************
/* Startup of PilotToTractor

DURATION          PilotToTractor 'TimeToTractor';

/*******************************************************************
```

```
/* Startup of Travel

DURATION          Travel 'TimeTractorTravel';

/*********************************************************************
/* Startup of PilotOutTractor

DURATION          PilotOutTractor 'TimeOutTractor';

/*********************************************************************
/* Startup of OrderC

ONDRAW TA1 PilotLineQ 'PilotLineQ+300';   / After spanning one steel
                                          tower pilot line will travel 300 m.
                                          i.e. it needs to travel a distance
                                          of conductor length to pullback the
                                          conductor, so, after each span the
                                          pilot line will travel a distance
                                          of 300m that is added to the
                                          previously covered distance till it
                                          completes the total distance
                                          required

/*********************************************************************
/* Startup of TractorPosition

DURATION          TractorPosition 'TimeTractorReposition';

/*********************************************************************
/* Activation of successors and routing of resources through Decision

STRENGTH          TA4 'PilotLineQ>=5000';
STRENGTH          TA2 'PilotLineQ<5000';

/*********************************************************************
/* Startup of PilotToConductr

DURATION          PilotToConductr 'TimePilotToCond';

/*********************************************************************
/* Startup of StartPulingCond

DURATION          StartPulingCond 'TravelOverTower';

/*********************************************************************
/* Startup of Anchor

ONDRAW AC2 AnchorCount 'AnchorCount+1';   / after anchoring the three
                                          phases the process terminates

DURATION          Anchor 'TimeConductorAnchor';

/*********************************************************************
```

```
/* Initialization of Queues, Running the Simulation, Presenting Results

INIT GroundMenQ NoOfGroundmenCrew;
INIT LinemenQ LinemenCrew;
INIT WinderOperatorQ WinderOp;
INIT PilotLineWindrQ PilotLineWinder;
INIT PilotLineGrndQ ConductorLength;
/ INIT TractorWaiting Tractor;
INIT SupervisorQ ConductorLength;
INIT TractorQ Tractor;
INIT ConductorQ ConductorLength;
/ INIT NextPilotSegmnt OrderG;
INIT TensionerQ NoOfTensioner;
/ INIT AnchorQ NoOfTensioner;
/ INIT PullBack NoOfTensioner;

SIMULATEUNTIL 'AnchorCount>=4';

PRINT StdOutput "%6.0f  %8.0f  %10.2f  %14.0f  \n" 11-Replications
TotalHourCost TotalTime TotalCost;
CLEAR;
ASSIGN Replications Replications-1;
WEND;

PRINT StdOutput
     "\n 95%% Confidence Interval on Project Duration is : [%6.2f, %6.2f] \n"
     'TimeStats.AveVal-Confidence[TimeStats.SDVal,0.95,TimeStats.nSamples]'
      'TimeStats.AveVal+Confidence[TimeStats.SDVal,0.95,TimeStats.nSamples]';
PRINT StdOutput
     "\n 95%% Confidence Interval on Project Cost is : [%12.1f, %12.1f] \n \n"
     'TCostStats.AveVal-Confidence[TCostStats.SDVal,0.95,TCostStats.nSamples]'
      'TCostStats.AveVal+Confidence[TCostStats.SDVal,0.95,TCostStats.nSamples]';


DISPLAY "Conductor Length =" ConductorLength;
DISPLAY "No of Conductor Tensioner =" NoOfTensioner;
DISPLAY "No of Groundmen Crew =" NoOfGroundmenCrew;
DISPLAY "No of Workers per Groundmen Crew =" GroundmenPerCrew;
DISPLAY "No of Linemen Crew =" LinemenCrew;
DISPLAY "No of Workers per LinemenCrew =" LinemenPerCrew;
DISPLAY "No of Pilot Line Winders =" PilotLineWinder;
DISPLAY "No of Tractors =" Tractor;
DISPLAY "No of Supervisors =" Supervisor;
DISPLAY "No of Winder Operator =" WinderOp;
DISPLAY "Pilot Line Winder Cost (SR/hr) =" PilotLineWinderCost;
DISPLAY "Tractor Cost (SR/hr) =" TractorCost;
DISPLAY "Conductor Tensioner Cost (SR/hr) =" ConductorTensionerCost;

REPORT;
```

APPENDIX C : *STROBOSCOPE Source Code for Project Example in Simulation of Time-cost Trade-off for the Construction of flow line pipes*

```
/*********************************************************************
/ Input Data:
/Following are the Activity ID numbers with their respectivedescription
/
/    ID.        Name
/   A10      MOBILIZTION
/   A20      SURVEY AND LAYOUT
/   A30      MATERIAL DELIVERY
/   A40      FABRICATE P.P.S.
/   A50      FABRICATE W/H AND TIE-IN PIPE
/   A60      FABRICATE REMOVABLE ANCHOR
/   A70      CONSTRUCT R.O.W.
/   A80      INSTALL P.P.S.
/   A90      CONSTRUCT REMOVABLE ANCHOR
/   A100     FABRICATE CP & TEST STATION
/   A110     FABRICATE GUARD RAIL
/   A120     FABRICATE KM MARKER
/   A130     SANDBALST /PAINT
/   A140     AS-BUILT DRAWING
/   A150     STRINGING
/   A160     PIPE WELDING
/   A170     INSTALL W/H PIPE SPOOL
/   A180     ROAD AND CAMEL XING
/   A190     TIE-IN PIPE SPOOL
/   A200     INSTALL GUARD RAIL & KM MARKER
/   A210     INSTALL CP/TEST STATION
/   A220     HYDROTEST
/   A230     FINAL TIE-IN
/   A240     CLEAN-UP & PUNCH LIST
/   A250     FINAL PAINT
/   A260     DEMOBILIZATION
/   D1       DUMMY ACTIVITY
/   D2       DUMMY ACTIVITY
/   D3       DUMMY ACTIVITY
/
/ The seed for the first stream. Comment out or change as appropriate
SEED 9111964;

/  The number of streams to use in duration statements
STREAMS 30;

/ Assignment of duration (days) to variables that later will be used
/ in calculating activity duration with pert distribution

SAVEVALUE D10* 7;
SAVEVALUE D20* 14;
SAVEVALUE D30A* 11;
```

```
SAVEVALUE D30B* 10;
SAVEVALUE D40* 24;
SAVEVALUE D50* 28;
SAVEVALUE D60* 20;
SAVEVALUE D70* 28;
SAVEVALUE D80* 14;
SAVEVALUE D90* 20;
SAVEVALUE D100* 12;
SAVEVALUE D110* 10;
SAVEVALUE D120* 7;
SAVEVALUE D130* 10;
SAVEVALUE D140* 38;
SAVEVALUE D150* 7;
SAVEVALUE D160* 21;
SAVEVALUE D170* 14;
SAVEVALUE D180* 21;
SAVEVALUE D190* 10;
SAVEVALUE D200* 6;
SAVEVALUE D210* 14;
SAVEVALUE D220* 6;
SAVEVALUE D230* 4;
SAVEVALUE D240* 7;
SAVEVALUE D250* 6;
SAVEVALUE D260* 7;

/ Assignment of cost (SR/day) to variables that later will be used in
/ calculating total activity cost by multiplying it to duration

SAVEVALUE C10* 2000;
SAVEVALUE C20* 12000;
SAVEVALUE C30* 6100;
SAVEVALUE C40* 11900;
SAVEVALUE C50* 24200;
SAVEVALUE C60* 12000;
SAVEVALUE C70* 24000;
SAVEVALUE C80* 12100;
SAVEVALUE C90* 15100;
SAVEVALUE C100* 6000;
SAVEVALUE C110* 9200;
SAVEVALUE C120* 5900;
SAVEVALUE C130* 11200;
SAVEVALUE C140* 4100;
SAVEVALUE C150* 17600;
SAVEVALUE C160* 25400;
SAVEVALUE C170* 17900;
SAVEVALUE C180* 24100;
SAVEVALUE C190* 12800;
SAVEVALUE C200* 12000;
SAVEVALUE C210* 5900;
SAVEVALUE C220* 23800;
SAVEVALUE C230* 11500;
SAVEVALUE C240* 11700;
SAVEVALUE C250* 6000;
```

```
SAVEVALUE C260* 3000;

SAVEVALUE N* 1;

/ The number of replication to perform.
VARIABLE nReplications 30;

/ Assuming duration of CPM activities are Pert. Using one row for the
/ duration parameters of each CPM activity. Place P0 in first column,
/ Mode in second, and P100 in third. Fourth column is for stream used


VARIABLE T10A  sPert[D10-1,D10,D10+1,1];
VARIABLE T10B  sPert[D10-1,D10,D10+1,2];
VARIABLE T20   sPert[D20-1,D20,D20+1,3];
VARIABLE T30A  sPert[D30A-1,D30A,D30A+1,4];
VARIABLE T30B  sPert[D30B-1,D30B,D30B+1,5];
VARIABLE T40   sPert[D40-1,D40,D40+1,6];
VARIABLE T50   sPert[D50-1,D50,D50+1,7];
VARIABLE T60   sPert[D60-1,D60,D60+1,8];
VARIABLE T70   sPert[D70-1,D70,D70+1,9];
VARIABLE T80   sPert[D80-1,D80,D80+1,10];
VARIABLE T90   sPert[D90-1,D90,D90+1,11];
VARIABLE T100  sPert[D100-1,D100,D100+1,12];
VARIABLE T110  sPert[D110-1,D110,D110+1,13];
VARIABLE T120  sPert[D120-1,D120,D120+1,14];
VARIABLE T130  sPert[D130-1,D130,D130+1,15];
VARIABLE T140  sPert[D140-1,D140,D140+1,16];
VARIABLE T150  sPert[D150-1,D150,D150+1,17];
VARIABLE T160  sPert[D160-1,D160,D160+1,18];
VARIABLE T170  sPert[D170-1,D170,D170+1,19];
VARIABLE T180  sPert[D180-1,D180,D180+1,21];
VARIABLE T190  sPert[D190-1,D190,D190+1,22];
VARIABLE T200  sPert[D200-1,D200,D200+1,23];
VARIABLE T210  sPert[D210-1,D210,D210+1,24];
VARIABLE T220  sPert[D220-1,D220,D220+1,25];
VARIABLE T230  sPert[D230-1,D230,D230+1,26];
VARIABLE T240  sPert[D240-1,D240,D240+1,27];
VARIABLE T250  sPert[D250-1,D250,D250+1,28];
VARIABLE T260  sPert[D260-1,D260,D260+1,29];

WHILE N<=50;     / starting of while loop, defining any high value for
                   comparing N against it

/ loading the CPM add-on with stroboscope engine
LOADADDON CpmAddon.dll;

/ Defining CPM activities with their respective duration, Using one
/ row for each activity with real activities defined with A and dummy
/ activities with  letter D

CPMACTIVITY D1 0;
CPMACTIVITY A10 T10A+T10B C10*(T10A+T10B);
```

```
CPMACTIVITY D2 T10A 0;
CPMACTIVITY A20 T20 C20*T20;
CPMACTIVITY A30 T30A+T30B C30*(T30A+T30B);
CPMACTIVITY D3 T30A 0;
CPMACTIVITY A40 T40 C40*T40;
CPMACTIVITY A50 T50 C50*T50;
CPMACTIVITY A60 T60 C60*T60;
CPMACTIVITY A70 T70 C70*T70;
CPMACTIVITY A80 T80 C80*T80;
CPMACTIVITY A90 T90 C90*T90;
CPMACTIVITY A100 T100 C100*T100;
CPMACTIVITY A110 T110 C110*T110;
CPMACTIVITY A120 T120 C120*T120;
CPMACTIVITY A130 T130 C130*T130;
CPMACTIVITY A140 T140 C140*T140;
CPMACTIVITY A150 T150 C150*T150;
CPMACTIVITY A160 T160 C160*T160;
CPMACTIVITY A170 T170 C170*T170;
CPMACTIVITY A180 T180 C180*T180;
CPMACTIVITY A190 T190 C190*T190;
CPMACTIVITY A200 T200 C200*T200;
CPMACTIVITY A210 T210 C210*T210;
CPMACTIVITY A220 T220 C220*T220;
CPMACTIVITY A230 T230 C230*T230;
CPMACTIVITY A240 T240 C240*T240;
CPMACTIVITY A250 T250 C250*T250;
CPMACTIVITY A260 T260 C260*T260;

/ Using one row for each Precedence relationship with predecessor
/ activity in column 1 and Successor activity in column 2.

PRECEDENCE D1 D2;
PRECEDENCE D1 A10;
PRECEDENCE D2 A30;
PRECEDENCE D2 D3;
PRECEDENCE A10 A20;
PRECEDENCE A10 A40;
PRECEDENCE D3 A50;
PRECEDENCE D3 A60;
PRECEDENCE D3 A120;
PRECEDENCE D3 A100;
PRECEDENCE D3 A110;
PRECEDENCE A20 A140;
PRECEDENCE A20 A70;
PRECEDENCE A20 A80;
PRECEDENCE A20 A90;
PRECEDENCE A70 A80;
PRECEDENCE A70 A90;
PRECEDENCE A40 A80;
PRECEDENCE A60 A90;
PRECEDENCE A50 A130;
PRECEDENCE A50 A170;
PRECEDENCE A30 A220;
```

```
PRECEDENCE A80 A150;
PRECEDENCE A90 A190;
PRECEDENCE A110 A200;
PRECEDENCE A100 A210;
PRECEDENCE A120 A200;
PRECEDENCE A130 A250;
PRECEDENCE A140 A260;
PRECEDENCE A170 A200;
PRECEDENCE A150 A160;
PRECEDENCE A180 A210;
PRECEDENCE A190 A220;
PRECEDENCE A160 A190;
PRECEDENCE A160 A180;
PRECEDENCE A200 A240;
PRECEDENCE A200 A250;
PRECEDENCE A220 A230;
PRECEDENCE A230 A240;
PRECEDENCE A230 A250;
PRECEDENCE A240 A260;
PRECEDENCE A250 A260;
PRECEDENCE A210 A240;

/ Performing replications of the model
CPMREPLICATE nReplications;
REPORT;

PRINT StdOutput
    "\n 95%% Confidence Interval on Project duration is : [%6.2f, %6.2f]"
    'ProjectDur.AveVal-Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]'
     'ProjectDur.AveVal+Confidence[ProjectDur.SDVal,0.95,ProjectDur.nSamples]';

PRINT StdOutput
    "\n 95%% Confidence Interval on Project Cost is : [%12.2f, %12.2f]"
    'ProjectCst.AveVal-Confidence[ProjectCst.SDVal,0.95,ProjectCst.nSamples]'
     'ProjectCst.AveVal+Confidence[ProjectCst.SDVal,0.95,ProjectCst.nSamples]';

IF D20==14;
    ASSIGN D20 10;
    ASSIGN C20 23000;
ELSEIF D30A==11;
    ASSIGN D30A 8;
    ASSIGN D30B 7;
    ASSIGN C30 10200;
ELSEIF D70==28;
    ASSIGN D70 21;
    ASSIGN C70 39500;
ELSEIF D80==14;
    ASSIGN D80 10;
    ASSIGN C80 23000;
ELSEIF D90==20;
    ASSIGN D90 14;
    ASSIGN C90 29800;
ELSEIF D130==10;
    ASSIGN D130 6;
```

```
    ASSIGN C130 24600;
ELSEIF D150==7;
    ASSIGN D150 4;
    ASSIGN C150 38800;
ELSEIF D160==21;
    ASSIGN D160 15;
    ASSIGN C160 44600;
ELSEIF D190==10;
    ASSIGN D190 7;
    ASSIGN C190 19600;
ELSEIF D200==6;
    ASSIGN D200 4;
    ASSIGN C200 22000;
ELSEIF D250==6;
    ASSIGN D250 4;
    ASSIGN C250 11700;
ELSE;
    BREAK;
ENDIF;

CLEAR;      / clearing of all system maintained variable values
ASSIGN N N+1;

WEND;       / End of while loop
```

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