FLEXIBLE SCHEDULING FOR CONSTRUCTION PROJECTS

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ABSTRACT

A successful project schedule is one of the prime keys to project success. The Critical Path Method (CPM) determines a rigid timeline of activities' execution ignoring resource related issues. Many techniques were developed to enhance CPM performance by taking advantage of the limited allowable flexibility that CPM provides. Resource allocation techniques assume limited resource availability and adjust the CPM schedule accordingly. Such practices will likely result in extended project duration which might not be so convenient to stakeholders. Where time is set as the sole constraint of a project, resource leveling techniques were developed to enhance the shape of the resource histogram by reducing its variations. Current resource leveling techniques took advantage of the only allowable flexibility provided by CPM – moving non-critical activities within available float. Researchers explored more options to further enhance resource leveling by taking into account activity splitting and using different computational approaches to enhance the computing time.

This research proposes new enhancements to CPM in order to explore more options in construction scheduling. The proposed approach introduces variability in the CPM schedule by allowing each activity to experience different scenarios of resource loading and working hours. Besides, the consequential changes in durations, productivity-related lags, and productivity losses are taken into consideration. In

addition, movements within available lags are included in the model as well. As each activity duration and resources are allowed to vary based on available scenarios, associated productivity losses are calculated to assure effectiveness of the solution. The model tries all the possible combinations of scenarios and finds the best fit for different objectives. In each objective targeted, many cost aspects of the projects are taken into consideration such as hiring/firing, liquidated damages, incentives, overhead and labor cost. This approach is modeled in Excel and solved using an add-in that solves non-linear integer problems called "*What'sBest*".

The results of this approach reflected new trade-offs in construction scheduling for different objectives. With resource leveling, the approach could achieve histograms with fewer variations, if not perfectly leveled, in exchange of marginal additional cost and less efficiency of workers. For resource allocation, the model outperforms the classical techniques resource allocation by attaining shorter schedules, smoother histograms, and lower overall project cost. The model also reflected better results in cost optimization and cost optimization with resource constraints. In other words, a new tri-polar trade-off is introduced among time, cost, and efficiency. This approach is referred to as "Flexible Scheduling".

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CHAPTER 1: INTRODUCTION

1.1 Research Background

A project is a temporary endeavor undertaken to create a unique product, service, or result [**1**]. Construction projects are particularly complex due to the fact that they consist of multi-disciplines that form interrelated sub-projects. The sequence of execution, in construction projects, requires coordination among various departments and disciplines in order to eliminate clashes in execution and interests. Hence, the need for adequate planning arose to pre-identify scope, resources, relations and sequence of activities in projects. The core objective of project management is to keep the workflow within the triangle-boundary of cost, time, and quality.

At the planning stage, the project, at different levels, is broken down to the simplest form of work packages. Each work package comprises a well-defined activity in terms of scope. Later on, these work packages are assigned certain amounts of resources and durations based on experience, references, or statistical analyses. At that stage, a rough estimate of the project total cost can be produced by going upwards in the Work Breakdown Structure (WBS) hierarchy. After defining all work packages, they are combined into a network that employs their interrelationships in order to construct a timeline for the project completion. The project network can be seen as a process chart where the arrows interconnecting work activities represent the physical constraints and the durations represent the time.

The Critical Path Method (CPM) is widely used in construction projects during planning and control phases. CPM relies on fixed durations and relationships among activities to determine the Critical Path (CP) and consequently determine the total project duration. Although CPM provides a logical and time-based schedule for the project, it ignores resource constraints such as manpower and finance. The CPM analysis is solely based on time and physical constraints and assumes unlimited availability of resources. In the current market conditions, resource constraints are likely to dominate over time constraints and as a result, CPM becomes an inconvenient stand-alone technique. Another drawback of CPM is that it does not incorporate productivity-related issues such as multi-tasking, Student Syndrome and Parkinson’s Law.

Other scheduling techniques such as Critical Chain Method (CCM) introduced enhancements to CPM by overcoming the aforementioned productivity-related issues. CCM reduces the activity duration by half and distributes the balance as buffers within and at the end of the project rather than having it within the activity. This practice is meant to impose a sense of pressure on workers to push them to work harder to complete the activity-at hand on time; therefore this technique is expected to overcome Student Syndrome. Besides crashing activities, CCM makes use of the balance buffer in the schedule by re-distributing it among activities such that multi-tasking, in the sense of having a crew working on more than one activity, is avoided. Afterwards, the remaining buffer is allocated to the end of the project and as float to accommodate any delays. Safety lags, if existed, are also removed resulting in shorter project durations.

Both CPM and CCM techniques have shortcomings. They are rigid in the sense that their inputs are fixed and their only flexible schedule attribute is activities float in the non-critical path – moving activities within their available floats. Also, CCM is weak because it is human behavior-reliant; this method depends on psychological effects to enhance productivity – overcoming Student Syndrome and Parkinson’s Law.

Controlling project cost expenditure is indeed a complex task. However, effective cost control can be achieved if direct costs such as material costs are assumed to remain constant. Indirect costs – such as labor, overhead and hiring/firing costs – consist mainly of resource-related expenditures and are influenced by how efficient and stable the resources are utilized. Thus, resource management, which has been ranked fourth in terms of risk factors for international contractors in the UAE [**2**], is a powerful attribute for construction projects that can result in major savings and/or good resource utilization.

Resources are related to project networks through histograms. Histograms are bar charts that reflect total resource demand in a given day. Histograms are very beneficial in reporting resource patterns throughout the lifecycle of the project. They can be used to identify the maximum number of required resources, and can be analyzed to determine hiring/firing patterns as well as hiring levels. If used in terms of monetary units, histograms can be used to determine the financial demand of the project.

As schedules are interconnected with resource histograms, histogram enhancements are usually achieved by schedule modifications such as resource allocation and resource leveling.

Resource allocation is scheduling under limited availability of resources. Consequently, histograms will have a ceiling which resource demands cannot exceed. The adjustment on schedules to accommodate with this particular limitation is through elimination of activity overlapping. This is achieved by delaying certain activities beyond their late start timing such that the maximum resource demand on a given day does not exceed the ceiling. Such practice usually ends up extending the project duration which might not be so convenient for stakeholders due to associated cost overruns or time being the main requirement of the project.

Resource leveling, on the other hand, deals with variations in resource demands throughout the project lifecycle. These variations reflect differences in resource needs among consecutive days in the project. These variations are costly because workers need to be transferred from a project to another, and because of work discontinuity-related losses. In the absence of alternative projects or when surplus takes place over a short time period, surplus workers are expected to be idle for the day. This incurs financial losses associated with paying for man-hours of zero earned value. These circumstances cause the project cost to inflate and reflect adversely on productivity indices. Not only that, but also transferring workers constantly can negatively affect their productivity and morale. Therefore, smoother histograms are desirable as they reflect both workers' stability and better utilization at different hiring levels. Enhancements made on the resource histogram are usually extracted from activities' float by moving non-critical activities. Moving activities within their float will ensure maintaining the original project duration and is expected to reduce peaks and fill gaps in order to approach as smooth as possible histogram.

Another trade-off in construction projects is project crashing (time-cost trade-off) which depends on shortening project duration by crashing critical activities. Depending on the contract content, normal-rate estimates might result in longer project duration than what is contractually desired. Hence, shortening critical activities in parallel critical paths through increasing resources or allowing overtime is performed to shorten the project duration up to the desired contractual date. However, shortening is an expensive practice and might result in severe cost inflation. Therefore, the shortening is done on gradual basis along with regular cost examination until reaching the minimum cost taking into consideration liquidated damages and crashing costs. Project crashing ignores its impact on resources and assumes time to be the only constraint.

In resource allocation, resource leveling and project crashing, relationships are not considered as variables. Certain relationships are, however, productivity-based and as a result modifications to working rates will result in relationship modifications. Relationships usually reflect the physical constraint that controls the sequence of activities. However, there are productivity-related relationships with certain amount of lags, e.g. Finish to start FS+2. The two-day lag is a translation to certain work percentage completion of the former activity after which the latter activity can begin. Thus, when performing crashing, the lags are expected to reduce to accommodate with the new faster execution of the activity. Project crashing ignores these consequential changes on the relationship and assumes all relations to be pure physical constraints.

It is a common practice among project managers to reduce overall project durations depending solely on increasing workers' productivity. However, such a practice has proven to be ineffective in many cases because it is human behavior-reliant. To manage the uncertainty in worker's productivity and to accommodate productivity losses, project managers tend to go with estimates that account for above average probability or they focus on improving the quality of supervision to improve workers performance [**3**]. It is evident from the aforementioned that there is a need to develop new scheduling techniques that will improve schedules and histograms given "normal-rate" performance.

1.2 Problem Statement

Many research works have been conducted in the area of project scheduling mostly focusing on introducing different kinds of enhancements to project schedules and histograms. Previous techniques have covered resource management (leveling and allocation) for different resources (financial and manpower) and have taken into account discounted money values and activity splitting. Researchers have also developed techniques of activity resource loading of both deterministic and probabilistic natures. In addition, using different computational approaches, researchers have developed models to find near optimal solution for scheduling problems using Heuristics. Previous results were based on the limited flexibility that

CPM provides as a scheduling technique by either moving activities within their float, delaying starting times or splitting activities.

Resource leveling and allocation require a minimum amount of flexibility in CPM in order to generate better schedules than the CPM's. In certain cases, classical leveling and allocation cannot be performed depending on constraints and schedule attributes resulting in no enhancements. Besides that, productivity-related relationships are expected to vary when varying the resource assignment to crash activity; however, current techniques do not incorporate such feature.

Some of the shortcomings of CPM are demonstrated in the following example along with the effect of incorporating activity crashing, activity relaxing and relationship variability. Table 1 summarizes project activities and their interrelationships.

Table 1
Activities List and Relationships

Activity	Normal duration	Total man-hours	Precedence	Relationship
Start	0	0	-	-
A	5	200	Start	FS
B	3	168	A	SS +3
C	6	240	B	FS
D	2	112	A	FS
Finish	0	0	-	-

Assuming 8 working hours per day, the number of resources (workers) to be assigned to each activity are summarized in Table 2.

Table 2
Resource Requirement Calculations

Activity	Number of required resources
A	= 200/(5*8) = 5
B	= 168/(3*8) = 7
C	= 240/(6*8) = 5
D	= 112/(2*8) = 7

Using CPM, the project network diagram is as shown in Figure 1.

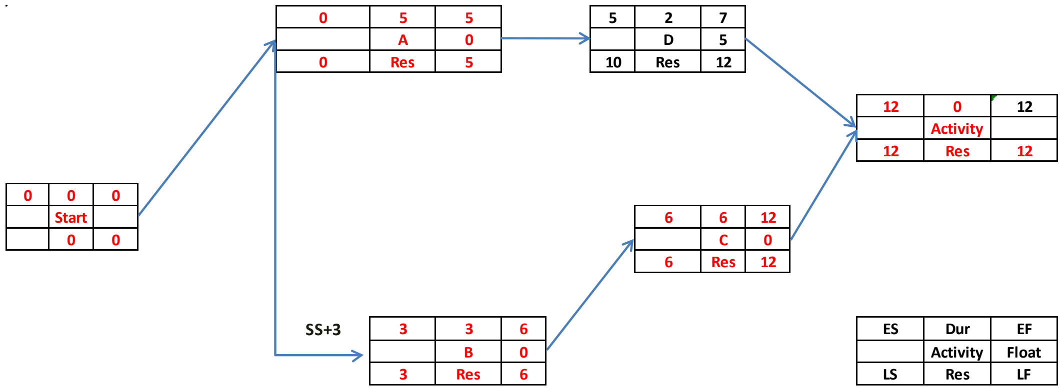

Figure 1. Project network diagram

As can be inferred from Figure 1, the total project duration is 12 days. Activities A, B & C form the critical path, while activity D is a non-critical with a float of five days. The resulting resource histogram (Figure 2) shows a maximum demand of 14 and hiring/firing count of 18.

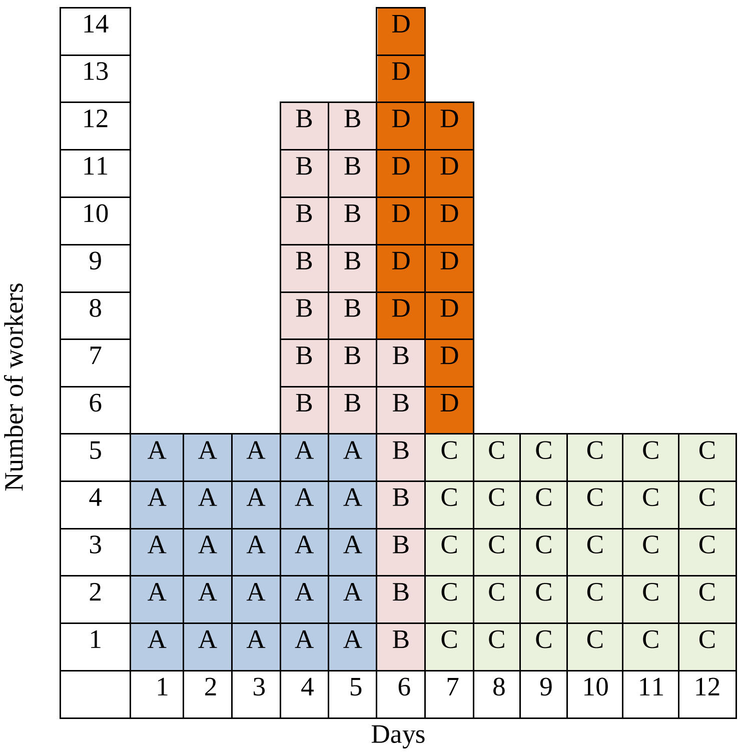

Figure 2. Project histogram

This example shows the rigidity of CPM by considering only fixed durations and relationships. Relationships such as SS+3 occurring between activities A & B are productivity dependent – it means activity (B) can start when (3/5=60%) of activity A is done.

Flexible Scheduling, however, allows durations to vary by allowing resource assignment to experience several options such as:

- Increasing number of resources assigned – Crowding; Shortening duration.
- Decreasing number of resources assigned – Relaxing; Duration elongation.
- Working overtime – Increasing number of working hours.

Crowding and overtime result in productivity losses that can be calculated as per Hinze [**4**].

Taking activity A as an example:

- Total requirement= 200 hours.
- Normal duration= 5 days.
- Resources = 200/(5*8)=5 workers.

Applying the above-listed options on activity A, the following scenarios can be extracted:

Scenario1 – Crowding:

If number of resources increased to 10 workers, duration will be:

- Crowding Efficiency=115%-15* $\left(\frac{10}{5}\right)$ =85%
- Duration= $\frac{200}{10*0.85*8}$ =3 Days.

Scenario 2 – Overtime:

If the number of workers is desired to remain the same, increasing number of working hours/days can contribute to the variation of activity duration.

If working hours increased to 10 hours per day:

- Overtime Efficiency= 100%-5$\left[\left(10\text{-}8\right)\right]$=90%
- Duration = $\frac{200}{5*10*0.9}$=4.44 Days.

If working hours increased to 12 hours per day:

- Overtime Efficiency= 100%-5$\left[\left(12\text{-}8\right)\right]$=80%
- Duration = $\frac{200}{5*12*0.8}$=4.2 Days.

Scenario 3 – Combination:

In addition to the above options, a combination of both can be used:

Using 8 workers and 10 hours per day:

- Crowding Efficiency=115%-15* $\left(\frac{8}{5}\right)$ =91%
- Overtime Efficiency= 100%-5$\left[\left(10\text{-}8\right)\right]$=90%
- Duration = $\frac{200}{8*10*0.91*0.9}$=3 Days

Assuming that scenario 3 was considered by increasing resources to 8 workers and 10 working hours, duration will be 3 days and consequently 60% of activity A will be completed in 1.8 days ≈ 2 days; therefore, the lag will change from +3 days to +2 days; This will reduce the project Duration to 11 days. Besides that, relationship between activities A and B can be changed to Finish-to-Start without affecting the project's duration.

Relaxation can be also considered, for example, activity D:

- Reduce from 7 workers to 2 workers.
- Duration =$\frac{112}{2*8}$=7 days

Figure 3 shows the project histogram after applying scenario 3 on activity A and relaxing activity D. The effect of scenario 3 reflected on the resource improvement rather on the project duration. The maximum demand reduced to nine and the hiring/firing count reduced to seven while the duration remained 12 days.

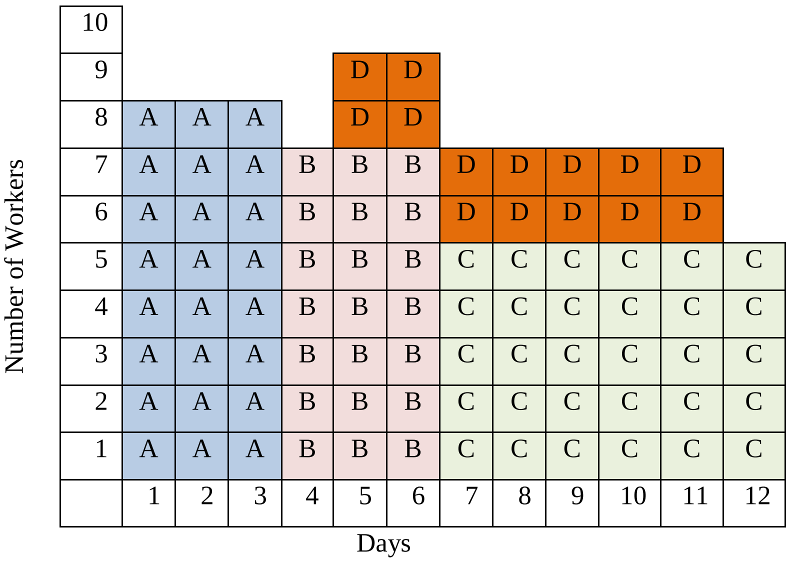

Figure 3. Project histogram after applying scenario 3 on activity A and relaxing activity D

Granting two activities the variability in demand would serve both objectives – reducing project time and resource leveling. The schedule flexibility is expected to increase if applied on all activities and good chances are that any objective can be completely fulfilled. If the objective was to minimize the total cost, cost of crowding, relaxing, overtime, overhead costs, liquidated damages, and hiring-firing costs can be compared against each other.

Improvements were achieved without using the option of moving non-critical activities within their available float. If activity D was moved one day in the last scenario, the histogram would have further improved.

Further improvements are expected to be achieved when modeling the approach using a computational technique that allows for optimizing the project schedule. Also, different objectives can be achieved using the same technique such as project crashing, resource leveling, and resource allocation.

With regards to the time-cost trade-off problems, current models and techniques focused on the cost of liquidated damages associated with project crashing and financial value of money to achieve the optimum or shortest project duration. However, these techniques did not relate estimation and scheduling processes so that the way resources are assigned serves the big picture of an optimized schedule by allowing different scenarios of activity resource loading. Not only that, but also, optimization techniques did not cover the consequential changes to certain logical relationships that result due to productivity changes of sequential activities. Besides, productivity issues were often dropped out of the equation which is believed to have a significant impact on the overall cost.

Hence, there is a need for a technique that explores more options imbedded within variability of resource assignment, working hours and applicable relationship variability. This technique should offer a better potential solution given different scenarios of resource assignment. Besides, labor productivity issues should be taken into consideration as well when considering deviations of normal estimates.

1.3 Objectives

The objective of this research is to develop a technique that explores better potential schedules than CPM's by taking into consideration resource assignment, working hours, and applicable relationships as variables. In addition, variations in resource assignment are subjected to productivity losses due to crowding and/or overtime. The developed technique examines all the possible combination of scenarios and finds the best one that serves different objectives. This technique is referred to as "Flexible Scheduling".

1.4 Research Significance

The main contributions of this research cover the following:

1. Introduction of a new approach that takes into consideration the variability of resource loading, working hours and lags in applicable relationships. This consideration allows exploring more options when enhancing the schedule. Based on the literature review, the developed approach is being considered for the first time.
    a. Based on normal rates estimations, durations will vary based on assigned resources and working hours; associated productivity losses will be accounted for.
    b. Relationship logics that depend on sequential activities productivities will have variability and hence more options.
2. This approach outperforms current optimization techniques that covers:
    a. Resource allocation.
    b. Resource leveling.
    c. Time-cost trade-off.
3. Addressing new kind of tri-polar tradeoff between cost, time, and workers efficiencies.
4. The model's output is very handful and detailed as it tells who, when, and for how many hours each worker should be assigned to each activity each day.

1.5 Research Methodology

This research study has started by defining assumptions and input functions for the model. It is assumed that relaxing activities has no effect on the productivity and that all activities are continuous and cannot split. Crowding and overtime efficiency equations are used as input functions in the model.

Because of its user-friendly interface and simplicity, Microsoft Excel was selected to construct the model. *What'sBest* add-in to Excel by Lindo has been used for model optimization due to its simplicity and strong optimization capabilities.

Although productivity equations are continuous, values for activity durations are more desirable in discrete form. Hence, it was decided to divide the solution process into two separate sub-processes: pre-modeling and modeling.

- Pre-Modeling: In this stage, all possible values for activities' resource assignment are examined along with their corresponding durations in order to manually segregate feasible options only with discrete values and minimum losses. Separating this process is beneficial as it allows for discrete solutions and, most importantly, allows for modification in productivity calculation without affecting the model.
- Modeling: Inputs from pre-modeling are incorporated in the model along with the network diagram that is interconnected with a histogram and a total cost representation of the project. By the end of this step, the model is all interrelated and any change of any value would have a cumulative and consistent reflection on the histogram, network or cost.

Initially, the model was expected to have a linear nature such that available global solving techniques can apply. However, and due to the following reasons, the model was then decided to have non-linear nature:

- Presence of logical non-smooth function (IF, AND, OR…etc.)
- Because flexible scheduling assumes duration, resources and applicable logic to be variables, it was unavoidable to have variables being constrained by other functions rather than constants. For the actual start, it has to fall between Early Start and Late Start that vary based on durations/resources assigned. Hence, a nonlinear model was found to be more suitable for Flexible Scheduling.

The model's variables, constraints and objectives examined are defined as follows:

- Variables:
  - Actual Start of activity.
  - Resources assigned per day for each activity.
  - Lags in productivity related relationships.
  - Working Hours = {8, 9, 10, 11, 12}.
- Constraints: (depending on the objective)
  - Project duration (Resource leveling)
  - Maximum daily resource demand (Resource allocation)
  - In applicable relationships, the lag should always exceed the percentage completion constraint (All objective).
  - Actual start should be equal to or larger than Early start (Resource Allocation and Cost Optimization)
  - Actual start is to be bounded by Early and Late Starts timing (Resource Leveling)
- Objectives:
  - Resource leveling (minimize variations).
  - Resource allocation (minimum duration given limited availability of resources).
  - Cost optimization (minimize project total cost).
  - Resource allocation and leveling.

What'sBest constrains each model to have one objective cell only and therefore, extreme objectives solutions might not be economically the best solution for each model. Hence, this shortcoming is overcome by fixating each extreme objective (leveling or allocation) to the minimum found value, and then minimizing the total project cost. This way, *What'sBest* will maintain the current solution and search for other cheaper combinations.

A hypothetical example is created to perform flexible scheduling and then compare against traditional techniques to show advantage. The example is modeled according to the former tasks and then run first by the current available techniques for each objective. After that, flexible scheduling was performed and results have reported outperformance over the current techniques.

Examples covering all objectives were extracted from previous researches and solved using flexible scheduling. In all circumstances, Flexible Scheduling reflected better results in extreme objectives.

For the sake of verifying the model and *What'sBest*, another set of examples covering all objectives was extracted from different research papers and was run using *What'sBest* solution using current scheduling techniques. All results were consistent with the ones in the research papers.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Once contractors receive the bid packages, intensive quantity takeoff practices are done to come up with consistent quantities of materials required for the project. After that, these quantities are assigned to work packages in the Work Breakdown Structure (WBS) to assign proper resources and estimate durations of executions. The WBS is usually developed by dividing the project scope into categories based on CSI divisions (Construction Specification Institute) and further into locations, then to functions and so on until reaching the simplest work unit. According to Hinze [**4**], the reliability of each work packages estimate depends solely on two factors: how accurate is the quantity surveying and thoughtful selection of productivity rates and unit costs.

While conceptual estimates are used for the owner/consultant to get a sense of the project total cost, detailed estimates are essential for the contractors to determine the bid price especially in lump-sum contracts. Such estimates are conducted by the estimator through breaking down project tasks into work packages and determine associated costs. Whereas direct cost elements, such as material costs, are easy to determine by getting supplier quotations, labor costs are difficult to approximate since they depend on workers productivities, construction methods, and so many other factors like weather, working environment…etc.

2.2 CPM and its Limitations

According to Oberlender [**5**], estimating activity duration depends on quantity and quality of work, number of people/equipment, level of workers skill, work environment and effectiveness of work supervision. Usually, durations are determined through one of three ways: expert judgment, historical performance data of the same company, or a standard reference. All of the sources of duration estimates are based, by a way or another, on historical performances on different levels. Uncertain durations are extracted by statistically analyzing former data for the company about this activity where the average duration can be determined and subjected to normal distribution to have variety in desired confidence levels.

Right after finalizing estimates, project scheduling requires establishing logical relationship between activities. Standard relationships are [**5**]: Finish-to-Start, Start-to-Start, Finish-to-Finish, and Start-to-Finish. Lags are added to these relations to accurately define sequence of work. After creating the network diagrams for the activities, forward and backward passes are applied to determine the following for each activity: Early Start (ES), Early Finish (EF), Late Start (LS), Late Finish (LF) and the available Float (FL). Consequently, the total project duration is extracted from the longest path through the network – Critical Path (CP).

The Critical Path Method (CPM) deals with predefined durations and relationships between activities and uses these as an input to determine the critical path, project duration, and the available float for non-critical activities. Resources are then loaded to the schedule and a histogram can be constructed representing the consolidated resource requirement per time unit.

The Critical Chain Method (CCM) comes with additions to CPM overcoming some of its shortcomings. Where CPM does not take into account Student Syndrome, Parkinson's Law, or Multi-Tasking issues, Critical Chain Project Management (CCPM) provided a solution to overcome these productivity issues: [**5**]

- Student Syndrome: People tend to put more effort into performing an activity when it approaches its deadline.
- Parkinson's Law that states work will always expand to consume all available time.
- Multi-Tasking: Performing two different activities of the same resource in the same time.

CCM surpassed Student Syndrome and Parkinson's Law difficulties by crashing all activities to half of its planned duration, moving the activities to the latest possible time, and distributing the balance duration, extracted from 50% reduction, as a buffer within and at the end of the project. CCPM also uses this buffer to assure that no multi-tasking is involved by adding buffers between activities to avoid multi-tasking of same resource on two different activities. This way, activity shortening will provoke workers productivity to enhance and work on an earlier deadline, and multi-tasking is eliminated for which workers and supervisors can focus on one activity at a time. According to Leach [**6**], CCPM improved project management and received remarkable feedbacks from contractors who implemented it – Honeywell, Lucent Technologies, Harris…etc.

Where the 50% reduction was extracted from the assumption that 50% will require shorter duration and the other 50% will require a longer duration [**6**], an optimized reduction amount, lower and upper bounds were determined and suggested and modeled to better fit each project's attributes [**7**].

Although The Critical Path Method (CPM) is widely used to schedule projects, it only provides time-constrained outputs in terms of starting and finishing times for activities. Where resource management plays important role in assuring smooth execution, CPM focuses only on time as a resource, assuming other tangible resources to be unlimited and ignoring associated costs with their utilization. Hence, approaches to optimize CPM schedules, with incorporation of tangible resource constraints, were developed to associate resource utilization with scheduling such as resource allocation and resource leveling.

2.3 Resource Allocation

Resource allocation refers to adjusting the CPM schedule, under the assumption of limited availability of resources and relaxed project duration, such that the sum of resource demands for activities in one day does not exceed that limit. Adjustments are done by altering start days of activities in order to for the histogram profile not to surpass the limited available resource. The effect of resource allocation is substantial and influential on the project execution and therefore becomes a key attribute in project success; it is essential to consider resource allocation when performing delay analysis in order to avoid risks [**8**].

Hinze [**4**] demonstrated two manual methods to allocate resources – Series Method and Parallel Method. The Series Method simply indicates that the activity can start once its precedence is done, provided that the utilization of available resources will not exceed the limited availability. In the occasions of conflicts, rules of thumb were demonstrated to regulate priorities among activities scheduling. The Series Method assumes continuity in activity execution; in other words, splitting is not allowed. On the other hand, The Parallel Method takes in consideration activity splitting to better utilize resources. Similar rules of thumb are used. Outputs of both techniques are more likely to result in longer project duration in order to keep up with the resource ceiling. Not only that, such manual techniques become very impractical if more than two different resources were utilized in a complex project.

Since projects in reality are very intense in terms of resources and activities involved, manual resource allocation techniques turned out to be time consuming and impractical. Leu & An-Ting Chen [**9**] proposed a new optimal resource-constrained construction scheduling model that combined both project duration uncertainty and resource allocation. Where the duration uncertainty was modeled using fuzzy logic, resource allocation was performed in a Genetic Algorithms-based model to find the near optimum solution. This model incorporated both resource scarcity and duration uncertainty and concluded a probabilistic time against resource limitation. This research did not include productivity losses due to duration variability but only based the duration on probabilistic values.

With a comparative advantage over Primavera Project Planner (P3) and MS Project, Lu, Lam, & Dai [**10**] introduced "Simulation-based Scheduling System (S3)" being modeled through simplified discrete simulation approach (SDESA) and the Particle Swarm Optimizer to optimize resource allocation such that it is achieved at the minimum project duration.

Moving to more complex scenarios in multi-project scheduling given that resource allocation is the prime concern in a program environment [**11**], models were developed to enhance the practicality and usability of resource allocation. Ghomi & Ashjari [**12**] presented a simulation model for multi-project resource allocation using a General Purpose Simulation GPSS's blocks in model generation.

2.4 Resource Leveling

The usual effect of resource allocation on schedules is time extension in the trade of working with the available resources. However, time is usually a prime constraint in construction projects and hence, extending project duration may be inconvenient to the client and costly to the contractor. Resource leveling is concerned with working with unlimited resources, strictly scheduled project, and variation in resource utilization. Variations in resource histograms accompany additional costs of transferring, discontinuity of work and other aspects. In addition, a perfectly leveled resource corresponds to the minimum number of workers required to execute the project. Resource leveling takes advantage of activities' floats by allowing moving of non-critical activities within their available float such that the resource histogram is smoothened and variations are minimized.

Hinze [**4**] demonstrated the manual solution for resource leveling using the Minimum Moment Algorithm procedure developed by Harris [**13**]. Depending on the maximum improvement factor achieved by moving the activity within its available float, activities starting dates are adjusted to enhance the resource histogram. This method will level "spikes" and "dips", however, it does not hit the optimum solution but rather an acceptable solution.

Harris [**14**] who developed the Minimum Moment Algorithm, introduced an alternative efficient manual technique called Packing Method. This method includes categorizing activities timelines into three sets: days which activity may occupy, days which activity must occupy, and days which the activity will never occupy. Although the method seems to be a bit more complex than minimum moment, it is very handy using Microsoft Excel. Comparatively, Harris [**14**] demonstrated how Packing Method surpasses his formerly developed technique such that peaks were reduced. In other words, Packing Method moved a step more towards optimal solution rather than settling on an acceptable one. Although this technique evolved better results than Minimum Moment, it still does not achieve the optimal solution and did not take into consideration other variables such as associated cost, activity splitting, or variable activity duration.

Hiyassat [**15**] developed further enhancements on The Minimum Moment Method by introducing a heuristic procedure that significantly reduced the amount of calculations needed and taking into consideration multiple resources. Hiyassat used the same example presented in former researches about Minimum Moment Algorithm and concluded that the results obtained were usually better than the traditional Minimum Moment results [**15**].

Easa [**16**] used integer-linear optimization to achieve resource leveling for construction projects for one resource. Having CPM and the initial input and setting the objective function to minimize deviations between resource demands, Easa [**16**] developed a model that optimizes resource leveling by allowing activities to move within their float in isolation of project duration. The developed model can be upgraded to include multiple resources and projects and finds exactly the optimum point given a relatively longer computational time that other methods. This method does not take in consideration activity splitting costs associated with leveling.

Lucko [**17**] developed a technique to analyze the criticality of linear schedules using singularity functions. The new approach maintains resources together and obtains an equation for resource histogram of a schedule. The research concluded that this approach surpasses pervious researches such that it maintains the relationship between activities and resources and reduces the numbers of variables.

Son and Mattila [**18**] presented a linear binary model for resource leveling. This research added a new kind of variability by allowing activities to split. The model reflected better results than CPM, however, caused project total cost to increase due to splitting cost. Also, in this paper, the authors demonstrated the effect of each activity's ability to split or not on the overall schedule. This research considered only one resource for the project.

Hariga & El-Sayegh [**19**] proposed a model that incorporates activity splitting along with resource leveling using mixed binary-integer programming. The model does not only aim to level the resource histogram, but also takes in consideration costs associated with activity splitting and aims to minimize the cost of stopping and resuming interrupted activities. The developed model does not take in consideration variability in activity duration in neither deterministic nor probabilistic points of view.

El-Rayes & Jun [**20**] developed two innovative resource leveling metrics that are used to quantify the impact of resource demands fluctuations – hiring/firing and idle time. In this model, two different objectives were set and then the optimal point combining both was reached. The first objective is to minimize the total fluctuation in the resource histogram (leveling) and the second was to minimize the overall peak demand in the construction project histogram. El-Rayes & Jun [**20**] used heuristic computational approaches to achieve the near optimal point. Where a perfectly leveled histogram is by default the histogram in which the peak demand is minimized, in-between scenarios might need to be optimized into a middle ground. It was concluded in the research paper that combining these two metrics resulted in a better desirable histogram. This model does not take in consideration cost associated with leveling such as hiring/firing cost or idle time cost.

2.5 Time-Cost Tradeoff

Other optimization objectives are set and achieved through the same techniques used for financial Resource Leveling. Chiu & Tsai [**21**] suggested an optimization approach to maximize the Net Present Value (NPV) taking into consideration liquidated damages and early finish bonus by moving activities within their float. This model moved activities such that payments are front loaded to maximize the net present value and minimize the effect of cash flow discounting.

Hegazy & Ersahin [**22**] developed a spread sheet for an overall cost optimization for schedules. Using excel and incorporating attributes such as resource allocation, resource leveling, time-cost tradeoff and cash flow analyses using Excel and Genetic Algorithms. The GAs technique was applied to settle on the optimal schedule that "minimizes the total project cost under time, cost, and resource constraints simultaneously". This model took in consideration simultaneous operations on the CPM along with the associated costs and provided the near optimum point given the objective of minimizing total project cost. This model however, did not cover uncertainty and variability of durations, risk, or activity splitting.

Cusack [**23**] demonstrated an integer-linear programming model to perform time-cost trade-offs. This proposed approach depended on less numbers of variables needed back at that time. Using software "Trans", Cusack managed to eliminate the need for any numerical analysis in the problem formulation. Although the model simplified time-cost trade-off problems, it did not take into consideration many factors such as discounted value of money or cost of varying the resource histogram.

Khang & Myint [**24**] attempted to evaluate a former research of time-cost tradeoff done by Babu & Suresh [**25**]. It was concluded that time-cost tradeoff model developed by Babu & Suresh using linear programming was useable; however, the quality part covers small part of long lists of considerations and is irrelevant to the problem.

John and Cengiz [**26**] demonstrated various function types representing crashing costs as in linear, piecewise linear or discrete. The model utilized both common objectives of time-cost tradeoff – minimizing the total cost and minimizing project duration. The model was simply constructed such that it can be easily run on commercial software like Excel. However, the cost attributes considered in the model were only direct and indirect costs. The model ignored hiring-firing costs, liquidated damages, or incentives.

Ammar [**27**] developed a model for time-cost tradeoff that takes into consideration discounted cash flows. While traditional time-cost tradeoffs only incorporate associated costs, Ammar has incorporated the changing value of money over time and concluded that the results differ from the traditional ones. Using mathematical programming and DCF's techniques, it was found that cost profile when crashing inflates and hence gives an advantage for crashing. This model however did not consider resource associated costs due to changes of speeding up the execution.

2.6 Labor Productivity

Productivity of workers is dependent on so many factors and is very complex to determine. Combinations of work environment, physical activities involved, supervision of workers, multi-tasking, interruption of work, crowding effects, long working hours, payment and so on, highly determine what the level of efficiency of a worker is. As per Hinze [**4**], losses due to crowding and overtime, can be calculated by the following equations:

- Crowding Efficiency = 115% - 15(Expanded Workforce/Normal Workforce)
- Overtime Efficiency = 100% - 5[(days-5) + (hours-8)]

Ng, et al. [**28**] conducted a research and found out that de-motivation of workers ranged from "5.1 to 13.6 man-hours/ week". It was also concluded that the loss being caused by material shortages, crowding, and rework are significant. Authors also suggested solution to these productivity losses such as management attention to the de-motivators. Also, it was concluded that total project value was found to be inversely proportional to time loss; demonstrating that when a project size increases, losses in terms of time decreases.

Alvanchi, et al. [**29**] have developed a "dynamic modeling tool" that is used to forecast productivity of workers under different working hours. This tool will facilitate for construction managers to calculate the long-term effects of productivity losses and allow them to make corrective actions. This research provided a long term behavior of productivity under certain overtime rate ignoring effects on the short-term. Figure 29 shows the resulting graphs demonstrating measurement of worker's productivity under overtime.

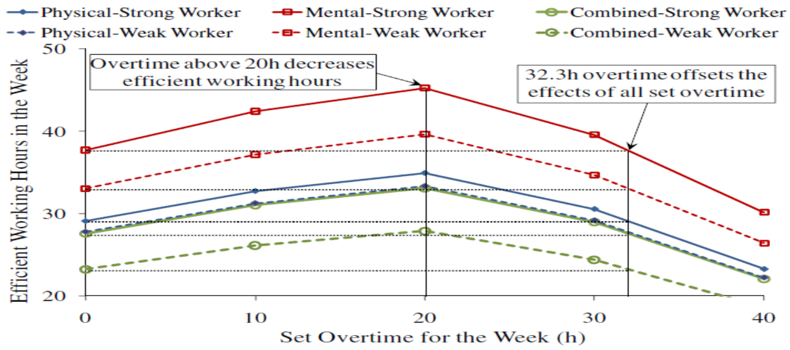

Figure 4. Productivity versus overtime [29]

CHAPTER 3: FORMULATION AND MODELING

3.1 Introduction

The main objective of CPM is to obtain the minimum project duration given the time that each activity will take to completion as well as the logic among these activities. CPM assumes unlimited availability of resources and works with fixed activity attributes (duration, resource requirement, and logic with predecessor/successor). Flexible Scheduling, on the other hand, allows for variable attributes in addition to free movement within the float for non-critical activities. In other words, Flexible Scheduling tries different resource assignment scenarios, different starting time within available float, and reflects the changes in applicable relationships.

In addition to achieving specific extreme objectives, Flexible Scheduling significantly enhances the overall functionality of CPM and allows for extended explorations of options and optimal points. In this scheduling method, different scenario permutations are applied on activities regardless of their criticality. This is expected to explore more options in terms of resources and consequently the project schedule in order to find better potential solutions.

Flexible Scheduling allows each activity to have different duration options through varying the amount of resource assignment and/or increasing working hours. In addition, the productivity losses associated with such variation are taken into consideration in terms of cost and productivity of workers.

3.2 Overview of Modeling Software

What'sBest add-in to Excel has been used to create and solve the Flexible Scheduling model. *What'sBest* is a powerful optimization tool for Excel-based spread sheets that has the capability to solve large-scale linear and non-linear complex problems. *What'sBest* surpasses other Excel optimization software because it allows the application of function-based constraints to model variables unlike other software packages that limit their models to constant constraints only. It is worth mentioning that *What'sBest* supports logical functions of Excel that are needed to complete the whole model such as (IF,AND,…,etc). In the case of non-linear models, it is hard to find a global optimum solution for the problem; however, *What'sBest* breaks the problem into linear convex sub-problems and keeps solving until reaching a mathematically proven global optimum point for each convex sub-model.

3.3 Model Assumptions

The assumptions used in constructing the Flexible Scheduling model are as follows:

- Activity resources are uniformly distributed throughout the activity duration.
- Losses associated with reducing number of workers will be neglected. This is due to the fact that when decreasing the number of workers, less supervision is expected to be required [**30**]. Hence, the minimal losses associated with reducing the number of workers are assumed to be covered by the savings on supervision costs.
- Activities are continuous and cannot be split.
- Costs will be assumed as follows unless noted otherwise:
  - Hiring/firing cost = 150 $/unit
  - Overtime pay rate = 1.5 x regular pay rate
  - Overtime can extend up to 4 hours (total of 12 working hours daily)

3.4 Construction of Flexible Scheduling Model

The introduction of options in scheduling project activities is based on allowing normal crew estimates and daily working hours to vary. This flexibility will make the area, which an activity occupies in the histogram, adjustable and more "liquidized" such that the overall histogram is at the desirable shape. In addition, the minimum physical constraint, demonstrated through logic lag, will vary according to the new duration in applicable relationships. Introducing such flexibility is intricate and thus, the whole process is split into two sub-processes – Pre-modeling, and Modeling.

3.4.1 Pre-Modeling

Figure 5 shows Flexible Scheduling pre-modeling steps. Each step is elaborated below.

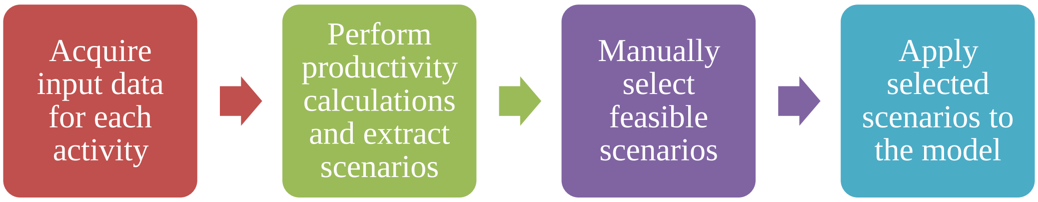

Figure 5. Process chart for Flexible Scheduling pre-modeling steps

3.4.1.1 Acquiring Input Data for Each Activity

Normal activity attributes reflect the crew size required to fulfill the total activity requirement under normal conditions. Values for such attributes can be extracted from published standards (such as RS-Means), company database, or expertise guess. Input values to the model in this research will be assumed to be given as inputs to the project.

3.4.1.2 Performing Productivity Calculations and Extracting Scenarios

Flexible Scheduling takes into consideration productivity losses that result from changing resource assignment from normal conditions (crowding) and from increasing number of working hours (overtime). In this model Hinze's equations [**4**] will be utilized to address the effect of modifications in crew size and extra working hours:

- Crowding Efficiency = 115% - 15($\frac{\text{Expanded Workforce}}{\text{Normal Workforce}}$) Eq. 1
- Overtime Efficiency = 100% - 5[(days – 5) +(hours – 8)] Eq. 2

In order to examine these productivity equations, new and old crew sizes (variables) and new durations (outputs) were normalized and plotted in Figure 6. As can be seen from Figure 6, the shortest duration that can be achieved using crowding is 45.37% of the original duration corresponding to 383% ratio increment on the original crew size. Any further increment in the crew size will have a reverse effect and increase the duration. This is due to the fact that efficiency will go below 50% at this increment rate and therefore the amount of loss will supersede the amount of gain.

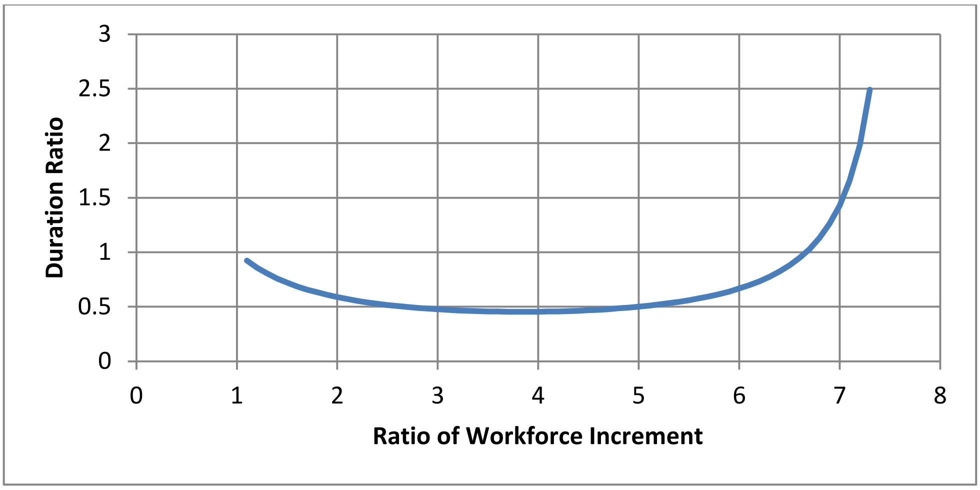

Figure 6. Crew size versus duration

On the other hand, overtime will introduce new scenarios for each activity by allowing each new crew size to experience different amount of working time.

Overtime and crowding productivity losses were combined in one graph where the resulting overall efficiency consists of their product. Figure 7 demonstrates the relationship between duration reduction ratio and crowding ratio under the effect of different working hours (8, 9, 10, 11 and 12). The maximum reduction that could be achieved by a combination of crowding and overtimes did not improve (45.37%). However, each crew size increment will have 4 different options in terms of working hours (8-12 hours).

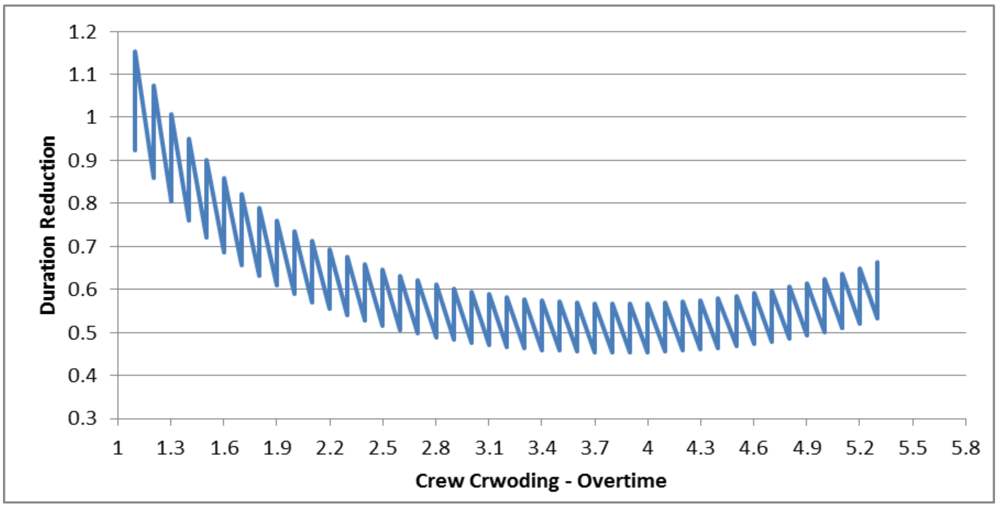

Figure 7. Overtime and crew crowding versus duration

Efficiencies are determined by linear equations and might result in fractional durations and/or resources, which is not convenient. Hence, obtaining possible scenarios for each activity will be pre-calculated based on integer increments in the resource and consequently the corresponding duration allowing up to -0.2 days tolerance. In other words, if the resource assignment fulfills the total requirement in 3.8 days, it will be considered as 4 days. Otherwise the scenario will be disqualified due to cost overruns and consequently it will be deemed infeasible.

The pre-calculated scenarios are to be determined by an Excel sheet that allows for integer-step reduction/increment in the activity's resource assignment and its corresponding duration. Manual selection is suggested so that the waste is minimized and to remain within the allowable tolerance.

$$\text{Ratio of Workers} = \frac{\text{New Crew Size}}{\text{Old Crew Size}} \qquad \text{Eq. 3}$$

Steps will be calculated through integer-step increments. For example, if the normal resource estimate is 2 workers, the increment steps would be 3, 4, 5, 6…etc. and vice versa for decrements. Each step will have 5 different working time options T = {8, 9, 10, 11, 12}.

Combining Hinze's equations [**4**], the new overall efficiency will be calculated using Equation 4. Equation 5 is used to calculate the new activity duration.

$$\text{Overall Efficiency} = \text{Crowding Efficiency x Overtime Efficiency} \qquad \text{Eq. 4}$$

$$\text{New Duration} = \frac{\text{Total Man-Hour Requirement}}{\text{(Ratio of workers)x(Old Crew size)(Overall Efficiency)x(T)}} \qquad \text{Eq. 5}$$

Figure 8 shows a sample Excel sheet for the productivity calculations explained above.

	A	B	C	D	E	F	G	H	I	J
1	Ratio	Crowding Effciency	T	Overtime Effeciency	Over all Effeciency	Actual	Effective	Duration	168	Total
2	=($I$2+1)/$I$2	=1.15-0.15*(A2)	8	=1-0.05*(C2-8)	=B2*D2*100	=$I$2*A2	=F2*E2/100	=$I$1/(G2*C2)	7	Labor
3	=($I$2+1)/$I$2	=1.15-0.15*(A2)	9	=1-0.05*(C3-8)	=B3*D3*100	=$I$2*A3	=F3*E3/100	=$I$1/(G3*C3)	=I1/(I2*8)	Duration
4	=($I$2+1)/$I$2	=1.15-0.15*(A2)	10	=1-0.05*(C4-8)	=B4*D4*100	=$I$2*A4	=F4*E4/100	=$I$1/(G4*C4)		
5	=($I$2+1)/$I$2	=1.15-0.15*(A2)	11	=1-0.05*(C5-8)	=B5*D5*100	=$I$2*A5	=F5*E5/100	=$I$1/(G5*C5)		
6	=($I$2+1)/$I$2	=1.15-0.15*(A2)	12	=1-0.05*(C6-8)	=B6*D6*100	=$I$2*A6	=F6*E6/100	=$I$1/(G6*C6)		
7	=A2+(1/$I$2)	=1.15-0.15*(A7)	8	=1-0.05*(C7-8)	=B7*D7*100	=$I$2*A7	=F7*E7/100	=$I$1/(G7*C7)		

Figure 8. Excel formulas for scenarios

3.4.1.3 Manual Selection of Feasible Scenarios

The manual selection process is based on the closest duration to an integer value. It is possible also to have two different durations corresponding to the same resource but with different working time (overtime). After calculating all the possible scenarios (Figure 8), the feasible ones are then manually selected based on rounding up with a tolerance of -0.2 days. The example sheet shown in Figure 9 shows the manually selected feasible scenarios based on the allowed tolerance.

Ratio	Crowding Effciency	T	Overtime Effeciency	Over all Effeciency	Actual	Effective	New Duration	512	Total
1.13	0.98125	8	1	98.125	9	8.83125	7.2	8	Labor
1.13	0.98125	9	0.95	93.21875	9	8.3896875	6.8	8	Duration
1.13	0.98125	10	0.9	88.3125	9	7.948125	6.4		
1.13	0.98125	11	0.85	83.40625	9	7.5065625	6.2		
1.13	0.98125	12	0.8	78.5	9	7.065	6.0		
1.25	0.9625	8	1	96.25	10	9.625	6.6		
1.25	0.9625	9	0.95	91.4375	10	9.14375	6.2		
1.25	0.9625	10	0.9	86.625	10	8.6625	5.9		
1.25	0.9625	11	0.85	81.8125	10	8.18125	5.7		
1.25	0.9625	12	0.8	77	10	7.7	5.5		
1.375	0.94375	8	1	94.375	11	10.38125	6.2		
1.375	0.94375	9	0.95	89.65625	11	9.8621875	5.8		
1.375	0.94375	10	0.9	84.9375	11	9.343125	5.5		
1.375	0.94375	11	0.85	80.21875	11	8.8240625	5.3		
1.375	0.94375	12	0.8	75.5	11	8.305	5.1		
1.5	0.925	8	1	92.5	12	11.1	5.8		
1.5	0.925	9	0.95	87.875	12	10.545	5.4		
1.5	0.925	10	0.9	83.25	12	9.99	5.1		
1.5	0.925	11	0.85	78.625	12	9.435	4.9		

Zero tolerance

The closest to 6 (-0.2 tol)

Figure 9. Selection process for feasible scenarios

3.4.1.4 Applying Selected Scenarios to the Model

All possible scenarios are to be segregated along with their corresponding resources, durations, overtime, and cost. This step aims to smoothen the modeling in Excel by having regulated cell addresses. The total labor cost will be calculated through Equation 6:

$$C_{Li}=[\text{Resource x Duration x 8 x (Cost / hour)}+(\text{Overtime x 1.5 x (Cost / hour)}] \quad \text{Eq. 6}$$

Figure 10 shows how the selected scenarios are arranged and applied to the model. This arrangement aims to facilitate utilizing these scenarios in the model.

		Scenario 1				Scenario 2				Scenario 3				Scenario 4			
	Total	Res	Dur	OT	Cost	Res	Dur	OT	Cost	Res	Dur	OT	Cost	Res	Dur	OT	Cost
A	200	5	5	0	20000	6	4	1	22800	8	3	3	30000	9	3	1	25650
B	240	5	6	0	24000	6	5	1	28500	7	5	0	28000	7	4	3	35000
C	512	8	8	0	51200	9	7	2	69300	9	6	4	75600	10	6	2	66000
D	160	5	4	0	16000	6	3	3	22500	7	3	0	16800	10	2	3	25000
E	280	5	7	0	28000	6	6	0	28800	6	5	4	42000	7	5	1	33250
F	256	8	4	0	25600	9	3	4	37800	10	3	2	33000	11	3	1	31350
G	384	8	6	0	38400	9	5	2	49500	10	5	0	40000	11	4	3	55000
H	448	7	8	0	44800	8	6	4	67200	9	6	2	59400	10	6	0	48000
R	256	8	4	0	25600	9	3	4	37800	10	3	2	33000	11	3	1	31350
P	168	7	3	0	16800	9	2	4	25200	10	2	2	22000	11	2	1	20900

Figure 10. Segregation of scenarios

3.4.2 Modeling

After coming up with all possible scenarios for each activity, a model is constructed using the scenarios and the CPM schedule as the main input. Table 3 lists the parameters used in the model.

Table 3
List of the Parameters Used in the Model

Symbol	Description	Symbol	Description
R_t	Total resource requirements at time (t)	C_{HF}	Cost of hiring workers for the whole project
O_{mi}	Resource assignment scenario (m) for activity (i)	C_{OH}	Project overhead expenses
D_{mi}	Corresponding duration of activity (i) to scenario (m)	I_N	Incentives for finishing the project earlier than agreed
C_{mi}	Cost associated with scenario (m) of activity (i)	C_{LD}	Project liquidated damages
AS_i	Actual start of activity (i)	C_T	Project total cost
ES_i	Early start for activity (i)	J_{ni}	n^{th} predecessor of activity (i)
LS_i	Late start for activity (i)	K_{ni}	n^{th} successor of activity (i)
EF_i	Early finish for activity (i)	L_{jin}	Logic lag between activity (i) and its n^{th} predecessor (J_{ni})
LF_i	Late finish for activity (i)	X_{ti}	Binary (0,1) coefficient
RC	Resource ceiling (i.e. vailable resources)	Z_{mi}	Binary coefficient for determination of scenarios
HF_t	Hiring/firing of resources at time (t)	T	Total project duration
C_{Li}	Labor cost for activity (i)	T_c	Project contractual duration

X_{ti} is a Binary coefficient that is equal to (1) when activity (i) is active, throughout the project timeline, at (t), (when $ES_i \leq t \leq EF_i$) and is equal to zero otherwise.

Figure 11 shows the sequence of the steps followed in the modeling stage. Each step will be explained further below.

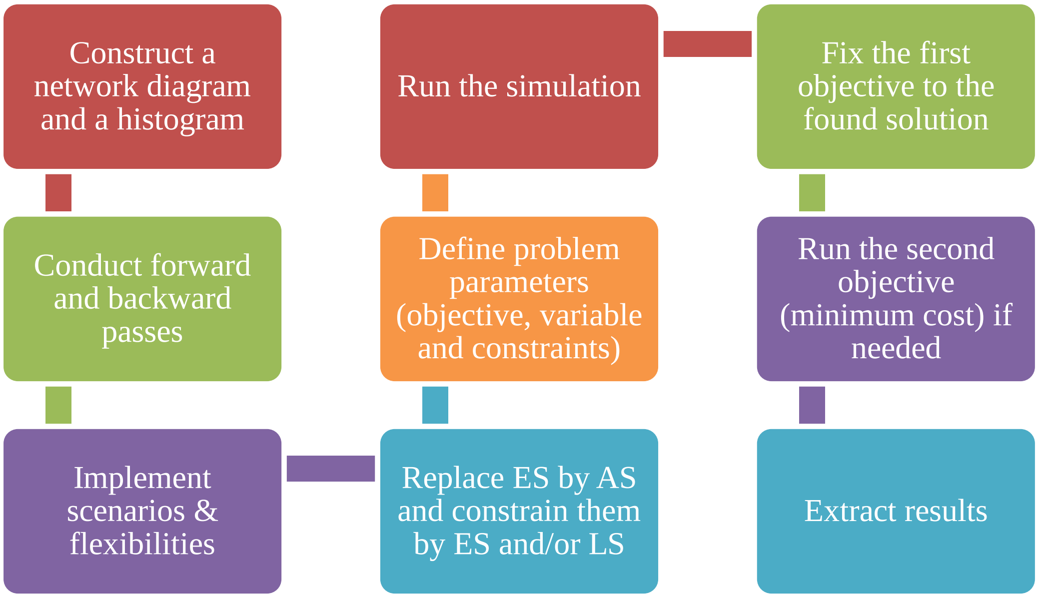

Figure 11. Process chart for Flexible Scheduling modeling steps

3.4.2.1 Construction of Network Diagram

The raw input for Flexible Scheduling model is the traditional CPM schedule (network diagram). Constructing a network diagram requires conducting forward and backward passes in order to come up with early and late time attributes for every activity.

- Forward pass:

$$ES_1 = 0 \quad \text{Eq. 7}$$

$$EF_i = ES_i + D_{mi} \quad \text{Eq. 8}$$

When determining (ES_i), there are three cases to consider depending on the logic between activities (i) and its predecessors (j): Finish-to-Start (FS), Start-to-Start (SS) or Finish-to-Finish (FF). In Flexible Scheduling, ES_i and LS_i are expected to vary in accordance with variations in activity durations. Hence, when allowing the activity to move within its free float, the movement has to be bounded by the functions forming ES_i and LS_i. Equation 9 demonstrates the function of ES_i.

$$ES_i=MAX\begin{cases} FS\rightarrow MAX([EF_{1ji}+L_{1ji}], [EF_{2ji}+L_{2ji}],\ldots, [EF_{nji}+L_{nji}]) \\ SS\rightarrow MAX([ES_{1ji}+L_{1ji}], [ES_{2ji}+L_{2ji}],\ldots, [ES_{nji}+L_{nji}]) \\ FF\rightarrow MAX([EF_{1ji}+L_{1ji}], [EF_{2ji}+L_{2ji}],\ldots, [EF_{nji}+L_{nji}])- D_{mi} \end{cases} \quad \text{Eq. 9}$$

D_{mi} will be obtained using Eq.13.

- Backward pass:

$$LF_n = T = EF_n \quad \text{Eq. 10}$$

$$LS_i=LF_i- D_{mi} \quad \text{Eq. 11}$$

$$LF_i=Min\begin{cases} FS\rightarrow MIN([LS_{1ki}- L_{1ki}], [LS_{2ki}- L_{2ki}], \ldots, [LS_{nki}- L_{nki}]) \\ SS\rightarrow MIN([LS_{1ki}- L_{1ki}], [LS_{2ki}- L_{2ki}], \ldots, [LS_{nki}- L_{nki}])+ D_{mi} \\ FF\rightarrow MIN([LF_{1ki}- L_{1ki}], [LF_{2ki}- L_{2ki}], \ldots, [LF_{nki}- L_{nki}]) \end{cases} \quad \text{Eq. 12}$$

D_{mi} will be obtained using Equation 13.

After conducting both passes on the network, the result will represent the CPM schedule of the project that reflects the minimum possible duration given each activity’s duration and logic connecting these activities.

3.4.2.2 Implementing Scenarios and Flexibilities

The next step is implementing the predetermined duration-scenarios for each activity and allowing for their alteration consistently with associated cost and resources. Although efficiencies and effects of re-sizing the crew are calculated through linear equations, it is not convenient to have fractions of neither workers, nor durations. Hence, the predetermined scenarios will be presented in the model as discrete values to assure feasibility of the solution. (Z_{mi}) will be a coefficient that accompany scenario (m) for activity (i). (Z_{mi}) is a binary coefficient (0,1). Three sets (determining duration, resources, and cost) will be generated for each activity carrying the same coefficients (Z_{mi}).

$$D_{mi} = Z_{1i} * D_{1i} + Z_{2i} * D_{2i} + Z_{3i} * D_{3i} + \cdots + Z_{mi} * D_{mi} \quad \text{Eq. 13}$$

$$O_{mi} = Z_{1i} * O_{1i} + Z_{2i} * O_{2i} + Z_{3i} * O_{3i} + \cdots + Z_{mi} * O_{mi} \quad \text{Eq. 14}$$

$$C_{mi} = Z_{1i} * C_{1i} + Z_{2i} * C_{2i} + Z_{3i} * C_{3i} + \cdots + Z_{mi} * C_{mi} \quad \text{Eq. 15}$$

D_{mi} is the m^th pre-determined duration scenario for activity (i) requirement; O_{mi} is the m^th predetermined resource scenario for activity (i); C_{mi} is the pre-determined cost associated with resource alteration (size and working hours) for the m^th scenario for activity (i).

In order to consistently assure one scenario at-a-time, the following constraint will apply:

$$\sum_{1}^{m} Z_{mi} = 1; \text{ Where } i= 1,2\ldots,n \qquad \text{Eq. 16}$$

After implementation of duration and resource variability, logic variability is to be utilized in the model. The kinds of relationships that Flexible Scheduling targets and allows changing are the ones with performance-based lag. In other words, if the logic is SS+2, it means that "2 time units" are a representation of percentage of work. Not only that, but also where there is no constraint to start right after fulfillment of the designated lag. Activities (A and B), where A's duration is 5 days, are related through a SS+2 relationship. This indicates that B cannot start unless minimum of 40% (2/5) of activity A is completed. This also indicates that B can still start any time after that. Flexible Scheduling allows for duration alteration and this is expected to affect the performance-based lags between activities.

$$L_{jin} \geq (\%\text{comp constraint}) \times D_{jni} \qquad \text{Eq. 17}$$

3.4.2.3 Replacing Early Start of Activities by Actual Start of Activities

In order to accommodate for activities movements within float, the start time of each activity is to be replaced with an actual start time that moves in isolation of the activity's dependent activities. Non-critical activities can move within their designated float without affecting the overall project duration. It is believed that such movements might have a positive effect on the resource histogram. However, because Flexible Scheduling allows durations and logic-relations to vary, the float will consequently vary and the constraints (ES_i and LS_i) will also change. Therefore, it is required that constraints applied on the activity start date to be functions rather than constants as in regular CPM. A new attribute will be introduced (AS_i) which represents the actual start activity (i). AS_i will be an integer variable bounded as per the Eq.18.

$$ES_i \leq AS_i \leq LS_i \quad \text{Eq. 18}$$

Where ES_i and LS_i can be determined from Eq. 3 and Eq. 5, respectively.

This way, each activity will have different sets of attributes (resources, duration and cost), variable logic depending on the duration scenario, and the freedom to move within the available float that is dynamically bounded by consistent functions of the activity's early and late start (ES_i and LS_i).

3.4.2.4 Defining Problem Parameters and Objectives

The new flexible network is ready for experimentation; however, the resource constraints are not yet implemented. Therefore, resource demands per time unit are to be calculated using Equation 19:

$$R_t = \sum_{i=1}^{n} (O_{mi} \times X_{ti}) \text{ ; Where t= 1, 2, 3…,T} \quad \text{Eq. 19}$$

Where R_t is the project resource requirement at (t) and X_{ti} is a binary (0,1) coefficient that is equal to (1) when activity (i) is active, through the project timeline, at (t), [when $AS_i \leq t \leq (AS_i + D_{mi})$] and is equal to zero otherwise.

The model now takes into consideration variable attributes for activities, variable logic-relations between activities, movement of activities within their available float, and also obtains projections of project resource requirement per time unit. The next step is utilizing these alterative project attributes to serve designated objectives along with their variables and constraints.

- Objectives:

This research examined several objectives and compared the results from current techniques and Flexible Scheduling. One of the challenges is a shortcoming of the software *What'sBest* as it only allows for one objective cell. This raises a problem of finding the cheapest solution for a given problem. In other words, if the objective is resource allocation, the given solution, although it is the shortest duration, might not be the most economical combination of scenarios. Hence, to overcome this shortcoming, a couple of objectives were set to each problem. The first one represents the main technical objective while the second one aims to minimize the cost given fixing the technical found solution. For example, fixing the minimum found duration in resource allocation to the found solution and then changing the objective to minimizing the cost. These two consecutive runs for the model will assure that the provided solution is both technical and financial.

In the following sections, each objective examined by the research will be explained and given set of modeling equations for both Flexible Scheduling and current classical methods.

Objective 1 – Resource Leveling

a. Classical Method

This objective aims to minimize variations in resource demands throughout the project's timeline such that hiring/firing practices are minimized. Resource leveling restricts the project duration to remain the same and therefore the only adjustments will be achieved through movement of activities.

Objective Function:

$$\text{MIN } (\textstyle\sum_{t=1}^{T} HF_t) \text{ ; Where } HF_t = |R_t - R_{(t-1)}| \qquad \text{Eq. 20}$$

Variables:

$$AS_i \text{ (Integer)}$$

Constraints:

$$ES_i \leq AS_i \leq LS_i$$

$$EF_n = T$$

b. Flexible Scheduling

Because Flexible Scheduling allows variable attributes for each activity, it opens new options for each activity and whether these variables will sum up and serve the bigger picture.

Objective Function:

$$\text{MIN } (\textstyle\sum_{t=1}^{T} HF_t) \text{ ; Where } HF_t = |R_t - R_{(t-1)}| \qquad \text{Eq. 20}$$

Variables:

$$AS_i \text{ (Integer); } Z_{mi} \text{ (Binary); } L_{jin} \text{ (Integer)}$$

Constraints:

$$ES_i \leq AS_i \leq LS_i \text{ ;}$$

$$L_{jin} \geq (\%comp\ constraint)\ x\ D_{jni} \text{ ;}$$

$$\sum_{1}^{m} Z_{mi} = 1$$

T= Fixed (cannot change from CPM)

Objective 2 – Resource Allocation

a. Classical Method

This objective aims to impose a ceiling on the histogram representing a limitation on the available resources. In order to accommodate with this limitations, activities start dates are moved forward such that overlaps are minimized and consequently peaks are also minimized. This technique usually results in project time extension.

Objective Function:

$$\text{MIN (T); where } T = EF_n = LF_n \qquad \text{Eq. 21}$$

Variables:

$$AS_i \text{ (Integer)}$$

Constraints:

$$Max(R_t) \leq RC$$

$$AS_i \geq ES_i$$

b. Flexible Scheduling

Not only the start date will vary and will be allowed to supersede its latest finish, but also durations, resources, and logic can vary.

Objective Function:

$$\text{MIN (T) Where } T = EF_n = LF_n \qquad \text{Eq. 21}$$

Variables:

$$AS_i \text{ (Integer); } Z_{mi} \text{ (Binary); } L_{jin} \text{ (Integer)}$$

Constraints:

$$Max(R_t) \leq RC$$

$$AS_i \geq ES_i$$

$$L_{jin} \geq (\%comp\ constraint)\ x\ D_{jni}$$

$$\sum_{1}^{m} Z_{mi} = 1$$

Objective 3 – Project Crashing

Project crashing is carried out in projects behind that are schedule to avoid liquidated damages resulting from expected late project delivery date. The duration crashing is usually attained through supplying more resources into the critical activities such that their duration is shortened and consequently the project duration reduced. Classical project crashing attains two objectives: shortest duration and optimum duration. Most researches focused on the crashing cost as a full package of crashing rather than how it was obtained. Not only that, project crashing is usually performed as a separate practice disregarding other resource constraints or cost overruns such as hiring and firing costs. Besides, project crashing considers crashing of critical activities only whereas Flexible Scheduling puts all activities under the spotlight exploring a potential more optimal solution under resource constraints.

Flexible Scheduling is expected to supersede classical methods in project crashing (time-cost trade-off) as it allows all activities to crash and relax with different resource options. In addition, Flexible Scheduling takes into consideration resource constraints (allocation and cost of hiring/firing). Besides, Flexible Scheduling allows applicable logic to vary given satisfaction of the physical constraint.

Hence, the crashing objective gets covered in the next objective (Cost Optimization) in the occasion of approaching the optimum duration. Regarding the minimum duration, the objective functions, variables, and constraints are technically the same as resource allocation in both classical and Flexible Scheduling techniques except for the resource ceiling and/or hiring/firing cost.

Objective 4 – Cost Optimization

Flexible Scheduling, by attaining new options, allows for a new kind of tradeoff among the efficiency (crowding & overtime), cost (including overtime), and project duration. Besides, new options are produced by allowing the logic to alter such that the objective might be better satisfied. When solving for resource extreme objectives, where cost is not a key factor, Flexible Scheduling offers good chances of finding a better solution. However, new cost attributes are associated with Flexible Scheduling such as overtime cost and efficiency losses which must be incorporated as new items into the total cost equation:

$$C_T = \text{Fixed Cost} + C_{HF} + C_{OH} + C_{LD} + \left(\sum_{i=1}^{n} C_{Li}\right) - I_n \qquad \text{Eq. 22}$$

Assuming that the fixed cost (procurement, site preparation,…etc.) will not be affected by the new variations in durations, resource assignment, and logic, the fixed cost will be omitted and the comparison will be against cost attributes that are function of time in addition to the activities labor cost:

$$C_T = C_{HF} + C_{OH} + C_{LD} + \left(\sum_{i=1}^{n} C_{Li}\right) - I_n \qquad \text{Eq. 23}$$

C_{HF} is the total cost of hiring and firing of workers (variations in the histogram) throughout the project:

$$C_{HF} = \left(\sum_{t=1}^{T} HF_t\right) \times \text{Unit Cost})\ ) \qquad \text{Eq. 24}$$

$$C_{OH} = T \times (\text{Overhead cost per time unit}) \qquad \text{Eq. 25}$$

$$C_{LD} = \begin{cases} (T > T_c) \rightarrow [T\text{-Contract Time } (T_c)] \times (\text{Liq. Cost per time unit}) \\ (T < T_c) \rightarrow 0 \end{cases} \qquad \text{Eq. 26}$$

$$I_n = \begin{cases} (T < T_c) \rightarrow [\text{Contract Time } (T_c)\text{-}T] \times (\text{Incentives per time unit}) \\ (T > T_c) \rightarrow \quad 0 \end{cases} \qquad \text{Eq. 27}$$

Fixed cost omission will not affect the total cost comparison as it is assumed to be isolated from changes.

Objective Function:

$$\text{MIN}\ (C_T)$$

Variables:

$$AS_i \text{ (Integer)};\ Z_{mi} \text{ (Binary)};\ L_{jin} \text{ (Integer)}$$

Constraints:

$$ES_i \leq AS_i;$$

$$L_{jin} \geq (\%\text{comp constraint}) \text{ x } D_{jni}\ ;$$

$$\sum_{1}^{m} Z_{mi} = 1;$$

$$\text{Max}(R_t) \leq RC$$

By implementing this objective function, variables, and constraints, Flexible Scheduling will attain the optimum cost duration taking into consideration resource constraints such as leveling and allocation.

Utilization of Flexible Scheduling allows for special objectives as well; the extended variability makes the CPM rigid schedule more viscous such that complex objectives become attainable. In markets like the UAE's, financing the project dominates as a constraint and supersedes the time as an essential objective. Other objectives may be derived from a high priority for resource leveling where the project managers want badly to have full utilization of the limited resources available. Such objectives can be achieved and have more likelihood to be approached by Flexible Scheduling.

Objective 5 – Minimum Duration for Perfectly Leveled Histogram

This objective aims to achieve 100% utilization of resources with exactly zero hiring and firing practices; in other words, a stable project. The final project duration might exceed the originally planned duration and also might be lower which will be a double win. This objective might come handy if the resources are translated into financial resources which will lead to new sub-objectives that can be modeled easily by marginal manipulation of parameters (Max NPV and leveled expenditure).

Objective Function:

$$MIN\ (T)$$

Variables:

$$AS_i \text{ (Integer)};\ Z_{mi} \text{ (Binary)};\ L_{jin} \text{ (Integer)}$$

Constraints:

$$ES_i \leq AS_i;$$

$$L_{jin} \geq (\%\text{comp constraint}) \times D_{jni}\ ;$$

$$\sum_1^m Z_{mi} = 1;$$

$$HF_t = 0$$

$$Max(R_t) \leq RC$$

Numerically, this objective is the same as resource leveling but aiming to completely eliminate variations given that the project duration is flexible.

3.5 Flexible Scheduling Example

In this section, a hypothetical example is used to demonstrate the Flexible Scheduling model and its results. Table 4 gives a summary of project activities, their attributes and interrelationships. Figure 12 and Figure 13 show the project CPM schedule and histogram, respectively.

Table 4
Hypothetical Project Activities List and Relationships

Activity	Total man-hour	Resource assignment	Normal duration	Logic act: logic + lag
A	200	5	5	-
B	240	5	6	-
C	512	8	8	-
D	160	5	4	-
E	280	5	7	A: SS+2
F	256	8	4	B: FS+0 E: FF+2
G	384	8	6	F,C : FS+0 H: FF+2
H	448	7	8	A,E: FS+0
R	256	8	4	G: SS+1 D: FS+0
P	168	7	3	G,R: FS+0

3.5.1 Project Information

The example project information are as follows:

- The client wants the project to finish in 20 days
- Liquidated damages are $1000/day
- Incentives for early finish $1000/day
- Regular man-hour pay rate = $35
- Hiring/Firing unit cost = $150
- Lags are performance-based lags and represent the minimum allowable lag.
- CPM's minimum duration = 22 days (refer to Figure 12)
- Network diagrams will follow this legend →

ES	Dur	EF
	Activity	
LS	Res	LF

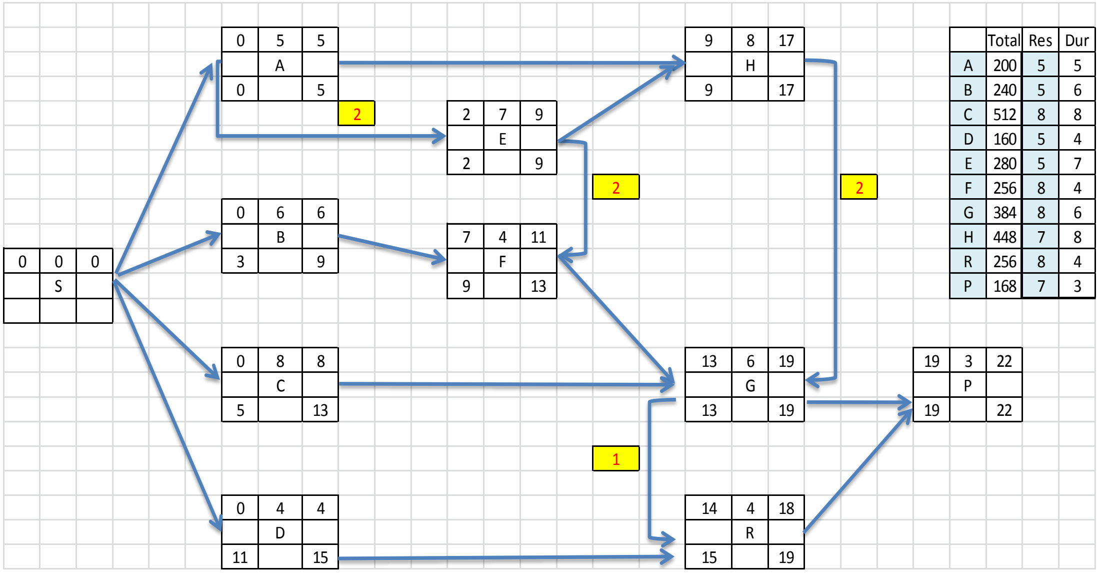

Figure 12. Hypothetical project network diagram

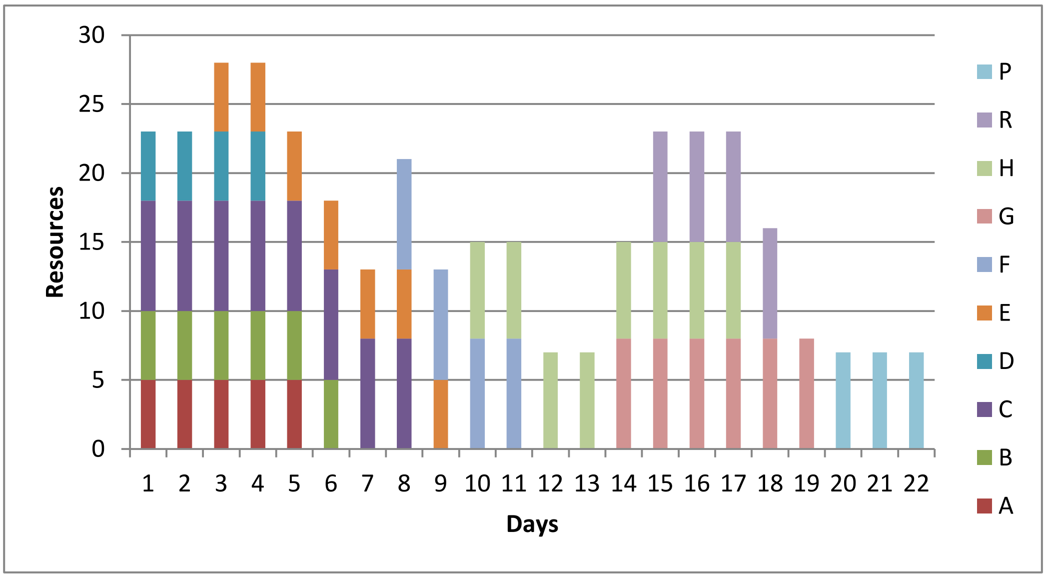

Figure 13. Hypothetical project histogram

The initial CPM schedule indicates that this project, under normal conditions, will finish in 22 days which is 2 days later than the contractual duration. Also, because CPM does not incorporate resource constraints and attributes, the corresponding histogram reflected a peak demand of 28 workers per day, and a total of 78 hiring/firing practices.

3.5.2 Applying Flexible Scheduling Model

As verification for the model, a sample calculation for obtaining time-related attributes from activities is demonstrated below.

Sample Calculation Using Activity G:

Activity G is related to several activities (Figure 14). Precedence activities (J_n) are "F: FS+0", "H: FF+2" and "C: FS+0". The successors (K_n) , the activities that "G" feeds a constraint into, are "R: SS+1" and "P: FS+0". These activities will contribute to the calculation of time-related attributes of activity G.

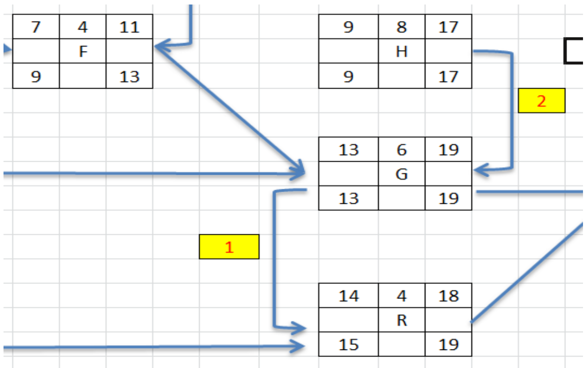

Figure 14. Location of activity G in the network

- Forward pass is conducted and ES_7 can be obtained using Eq. 9:

$$ES_7 = MAX\begin{cases} FS \rightarrow \ MAX([\,11 +\ 0], [\,8 +\ 0],) \\ SS \rightarrow \ None \\ FF \rightarrow \ MAX([\,17 +\ 2]) -\ 6 = 13 \end{cases}$$

$$ES_7 = MAX\begin{cases} 11 \\ 13 \end{cases} = 13$$

$$EF_7 = \ 13 +\ 6 = 19$$

- Backward pass is conducted and LF_7 can be obtained using Eq. 12:

$$LF_7 = Min\begin{cases} FS \rightarrow \ MIN([\,19 -\ 0\,]) \\ SS \rightarrow \ MIN([\,15 -\ 1\,]) +\ 6 \\ FF \rightarrow \ NONE \end{cases}$$

$$LF_7 = Min\begin{cases} 19 \\ 20 \\ \end{cases} = 19$$

$$LS_7 = \ EF_7 -\ 6 = 19 - 6 = 13$$

The duration used in forward and backward passes are the normal durations given as an input and implemented in the CPM network. After conducting both passes on all activities, the latest finish date was found to be 22 days.

Using Eq. 23, the total cost of the project would sum to:

$$C_T = C_{HF} + C_{OH} + C_{LD} + (\sum_{i=1}^{n} C_{Li}) - I_n$$

$$C_T = (78 * 150) + (22 * 2000) + (1000 * 2) + (2904 * 35) - 0$$

$$C_T = 159340\ \$$$

This total cost ignores fixed cost and will be used for comparison and optimization which is conservative assuming that manipulation of the schedule will have minimal effect on the fixed cost. Apparently the current schedule is not ideal as its duration exceeds the contractual duration with cost overruns in resource fluctuations and liquidated damages.

To model activities' movements within float, the schedule must be exploded by replacing all the ES_i cells by AS_i with equal initial values (Figure 15). The actual cells in the network diagram in excel will be referred to other cells that are tabulated in order to be properly constrained.

Act	ES	Const	As	Const	LS
A	0	=<=	0	=<=	0
B	0	=<=	0	<=	3
C	0	=<=	0	<=	5
D	0	=<=	0	<=	11
E	2	=<=	2	=<=	2
F	7	=<=	7	<=	9
G	13	=<=	13	=<=	13
H	9	=<=	9	=<=	9
R	14	=<=	14	<=	15
P	19	=<=	19	=<=	19

Figure 15. Actual start times of activities

Each AS_i is bounded by the ES_i and EF_i which are extracted from the same equations used to find the initial values. These constraints will assure that no limitation or logic will be breached regardless of the change.

After allowing activities to enjoy free movement within their float, scenarios are to be derived for each activity giving the corresponding duration and cost for each scenario.

Sample Calculation Using Activity A:

- Scenario 2 – Using 6 workers and 9 hours per day

$$\text{Crowding Efficiency} = 115\% - 15\left(\frac{6}{5}\right) = 97\%$$

$$\text{Overtime Efficiency} = 100\% - 5(9-8) = 95\% \,.$$

$$\text{Overall Efficiency} = 0.97 \text{ x } 0.95 = 0.9215$$

$$\text{New Duration} = \frac{200}{\left(\frac{6}{5}\right)\text{x}(5)(0.9215)\text{x}(9)} = 4.0 \text{ days}$$

$$C_L = (6\times8\times4\times35\$) + (6\times1\times4\times35\times1.5) = 7980\$$$

O2	Res	6
	Dur	4
	OT	1
	Cost	7980
O3	Res	8
	Dur	3
	OT	3
	Cost	10500
O4	Res	9
	Dur	3
	OT	1
	Cost	8977.5
O5	Res	10
	Dur	3
	OT	0
	Cost	8400

Figure 16. Scenarios for activity A

Schedule Enhancements:

I. Resource Leveling

There are several enhancements that can be done to CPM schedules when relating time-related attributes with resources. Arbitrary variations in resource histograms are not desirable due to its negative effect on productivity of workers and consequently cost overruns. Hence, resource leveling is a practice that aims to enhance the resource histogram (minimize variations) by moving non-critical activities within their available float. Modeling wise, after exploding the network diagram, activities will be able to use its float such that the histogram is smoother. However, the model should prevent the project duration from extending further and therefore is the constraint on the latest finish date:

Objective Function for classical leveling:

$$\text{MIN } (\sum_{t=1}^{T} HF_t) \text{ ; Where } HF_t = |R_t - R_{(t-1)}|$$

Variables:

$$AS_i \text{ (Integer)}$$

Constraints:

$$ES_i \leq AS_i \leq LS_i;$$

$$EF_n = LF_n = 22 \text{ days}$$

After running the model for classical leveling, the best shape that could be achieved is as shown in Figure 17 and Figure 18.

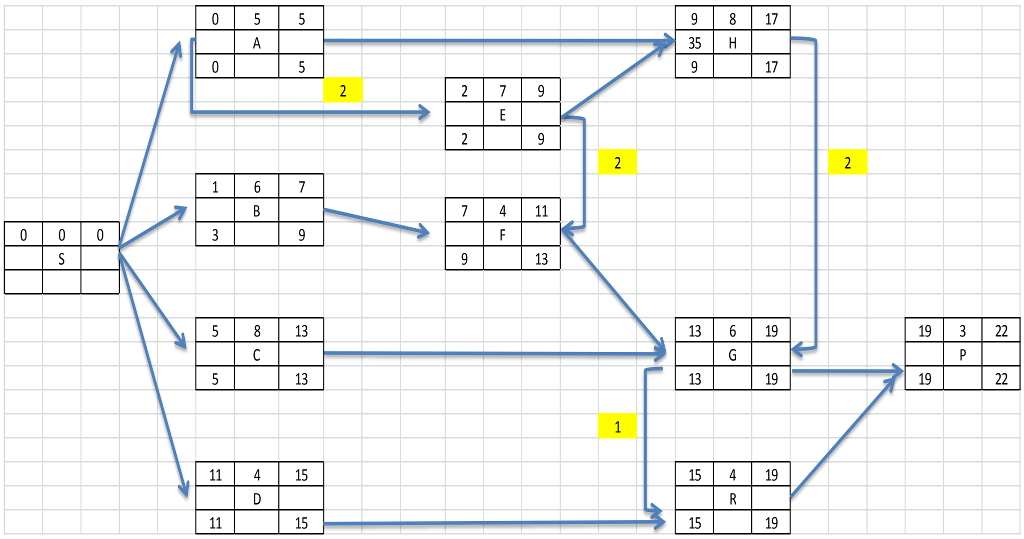

Figure 17. Network diagram after classical leveling

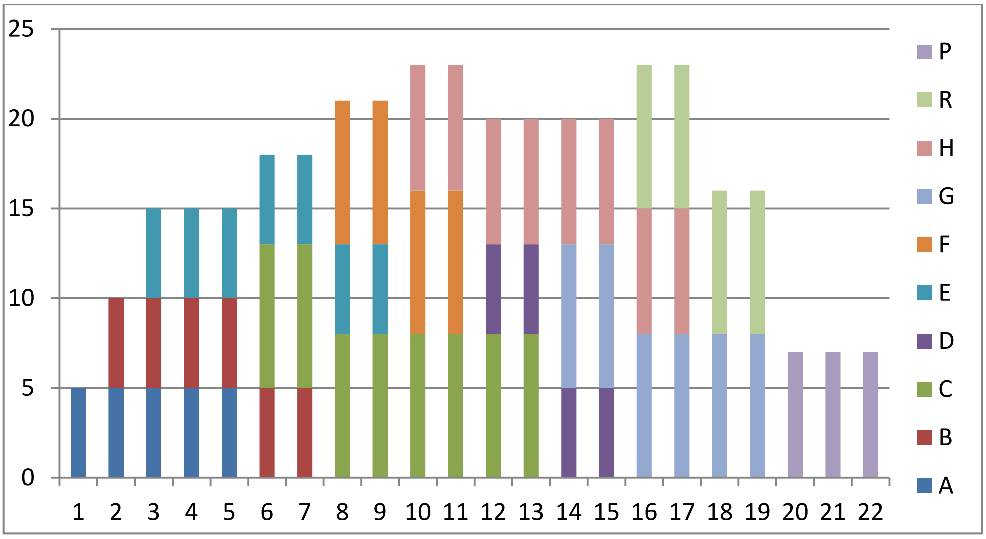

Figure 18. Histogram after classical leveling

Movement of activities reflected an improvement on the histogram. The maximum demand dropped from peaking at 28 to 23 workers (17.9% improvement). Also, the total of hiring and firing count dropped from 78 to 40 (48.7% improvement). There is no need to re-run for minimum cost because the minimum total cost is achieved by minimizing variations – leveling.

Now, the scenarios (crashing/relaxing) are to be set as adjustable in addition to the logic lags. All the scenarios are set to variables in addition to the bounding constraints of the actual start.

The following objective function, variables, and constraints are to be applied:

Objective Function:

$$\text{MIN } (\textstyle\sum_{t=1}^{T} HF_t) \text{ ; Where } HF_t = |R_t - R_{(t-1)}|$$

Variables:

AS_i (Integer); Z_{mi} (Binary); L_{jin} (Integer)

Constraints:

$$ES_i \leq AS_i \leq LS_i$$

$$;L_{jin} \geq (\%comp\ constraint)\ x\ D_{jni}$$

$$\sum_{1}^{m} Z_{mi} = 1$$

T= 22 days

After running the model, the network shown in Figure 19 was found to be the best solution. The corresponding histogram is shown in Figure 20.

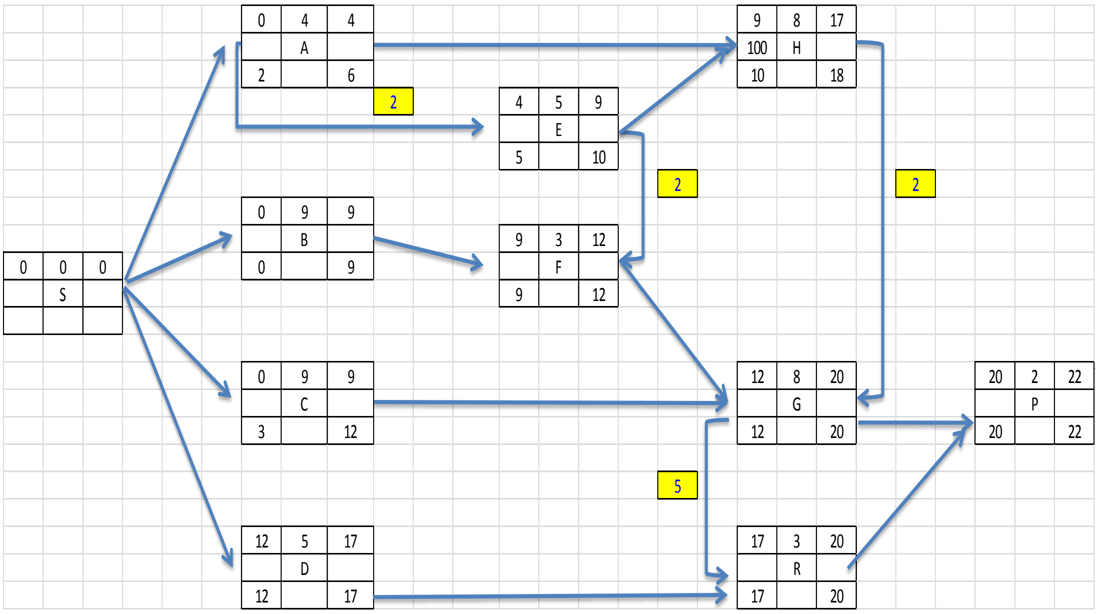

Figure 19. Network diagram after leveling using Flexible Scheduling

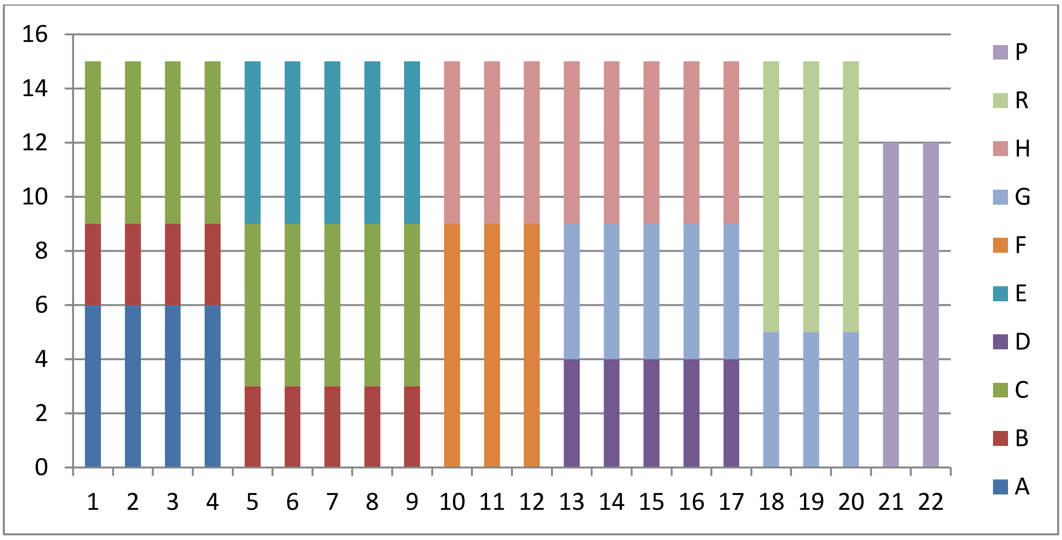

Figure 20. Histogram after leveling using Flexible Scheduling

Referring to Figure 20, the resulting histogram dramatically superseded the classical method. The variations (hiring/firing count) in the histogram dropped from 78 to 3 (improvement by 96.1%) with a peak demand of 15 workers dropping from an initial value of 28 workers (46.4% improvement). The best leveled histogram was achieved through specific scenarios, logic, and actual start time as shown in Figures 21, 22 and 23.

	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
Za	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Zb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Zc	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Zd	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Ze	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Zf	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Zg	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Zh	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Zr	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Zp	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 21. Selection of scenarios after leveling using Flexible Scheduling

Act	ES	Const	As	Const	LS
A	0	=<=	0	<=	2
B	0	=<=	0	=<=	0
C	0	=<=	0	<=	3
D	0	<=	12	=<=	12
E	2	<=	4	<=	5
F	9	=<=	9	=<=	9
G	12	=<=	12	=<=	12
H	9	=<=	9	<=	10
R	17	=<=	17	=<=	17
P	20	=<=	20	=<=	20

Figure 22. Actual start times
(leveling using Flexible Scheduling)

	Res	Dur	OT	Cost
A	6	4	1	22800
B	3	9	2	29700
C	6	9	4	75600
D	4	5	0	16000
E	6	5	4	42000
F	9	3	4	37800
G	5	8	4	56000
H	6	8	3	60000
R	10	3	2	33000
P	12	2	0	19200

Figure 23. Activity attributes
(leveling using Flexible Scheduling)

The best solution given the constraints set above was achieved by scenarios totally different than the normal values (Figure 21). The model could achieve a new combinations of scenarios, logics lags (L_G changed from 1 to 5), and movement within given float that corresponds to the best schedule. The final output presents detailed solution for the leveling problem – How many workers, how many days, and how many working hours for each activity.

Because the number of variables increased given the non-constant constraints for actual start times, the calculation time increased compared to the classical leveling. Not only that, the cost (due to overtime higher pay rate) also increased by 35% percent. This particular case demonstrates a trade-off between resources stability (leveling) and cost which might help the decision maker to set priorities and decide whether to settle for an extreme solution or a midway optimum one. In other words, Flexible Scheduling presented a wider space of solution with new trade-off decision making.

Another run was initiated on the same model with the following changes: Total variations were fixed to three hiring-firing, and the objective changed to minimizing the total cost. Intending to find the cheapest solution that corresponds to the minimum variations, the given solution was found to be the cheapest.

By running these consecutive objectives on the same model in addition to the added constraint on the second run, the best objective at the best economic value is found.

II. Resource Allocation

Some projects are bounded by constraints other than time and cost – resource constraint. One of CPM's common problems is limitation of resources that is not taken into consideration. Resource allocation aims to reduce peak demands by delaying start timings for activities such that overlaps and peaks are reduced. Resource allocation usually ends up extending the project's duration which might not be convenient to the client or/and consultant. The following inputs will be implemented in the model in accordance with resource allocation and this particular project:

Objective Function:

$$MIN\ (T)\ (T = EF_n = LF_n)$$

Variables:

$$AS_i\ \text{(Integer)}$$

Constraints:

$$Max(R_t) \leq 12$$

$$AS_i \geq ES_i$$

In classical resource allocation, start dates are subjected to one-sided boundaries which is the Early Start such that it allows the activity to be delayed without breaching its relationships with its precedence. The results of classical resource allocation are shown in Figures 24 and 25.

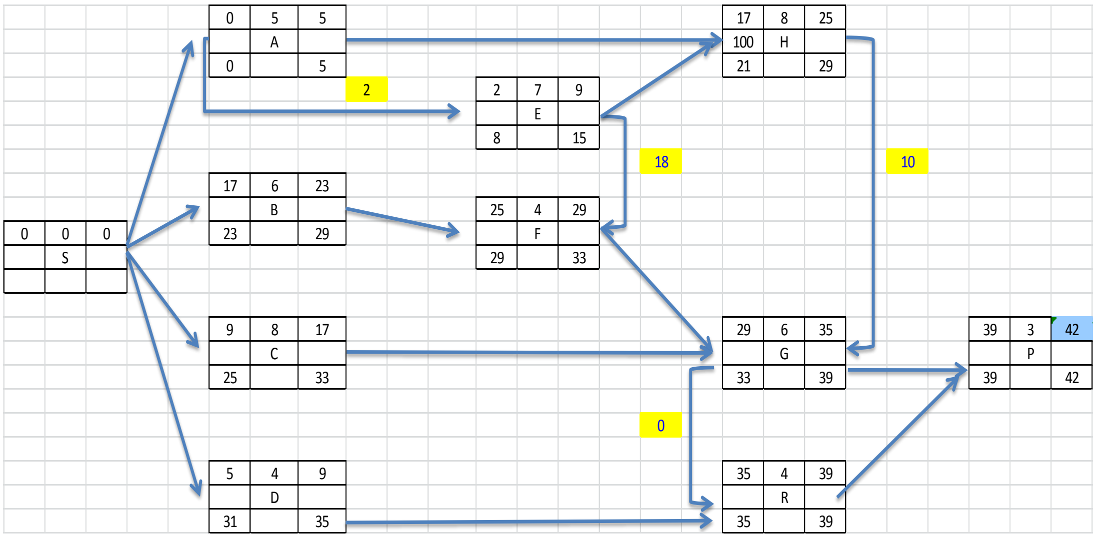

Figure 24. Network diagram after classical resource allocation

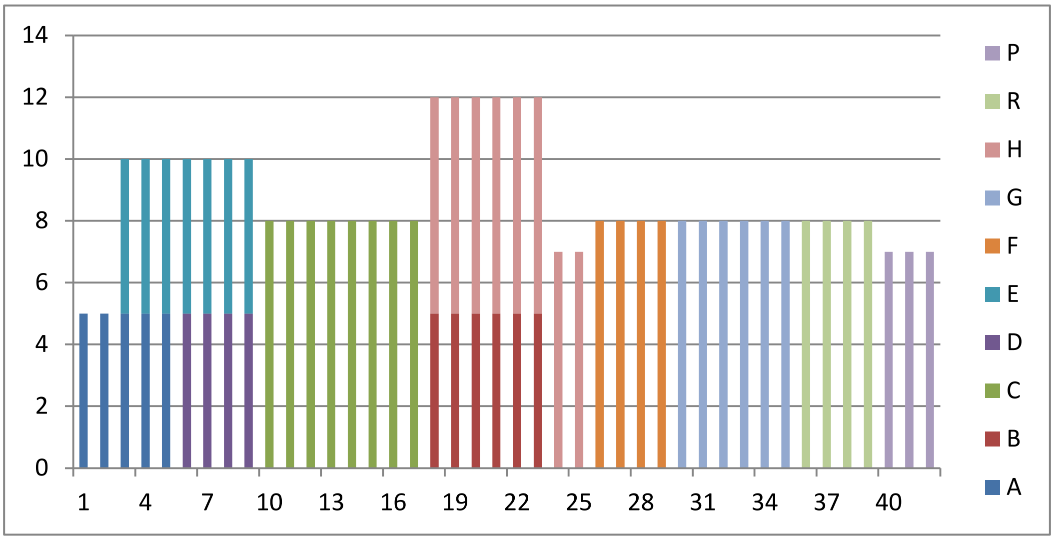

Figure 25. Histogram after classical resource allocation

The resulting project duration (42 days) reflected a dramatic increase amounted at (190.9% increment) which consequently increased the cost by 32% (due to overhead, hiring-firing and liquidated damages cost). In addition, the project histogram reflects more variations in demands.

Using Flexible Scheduling attributes:

Objective Function:

$$\text{MIN (T) } (T = EF_n = LF_n)$$

Variables:

$$AS_i \text{ (Integer); } Z_{mi} \text{ (Binary); } L_{jin} \text{ (Integer)}$$

Constraints:

$$\text{Max}(R_t) \leq 12$$

$$AS_i \geq ES_i$$

$$L_{jin} \geq (\%comp\ constraint)\ x\ D_{jni}$$

$$\sum_{1}^{m} Z_{mi} = 1$$

After running the model, the network shown in Figure 26 was found to be the best solution. The corresponding histogram is shown in Figure 27.

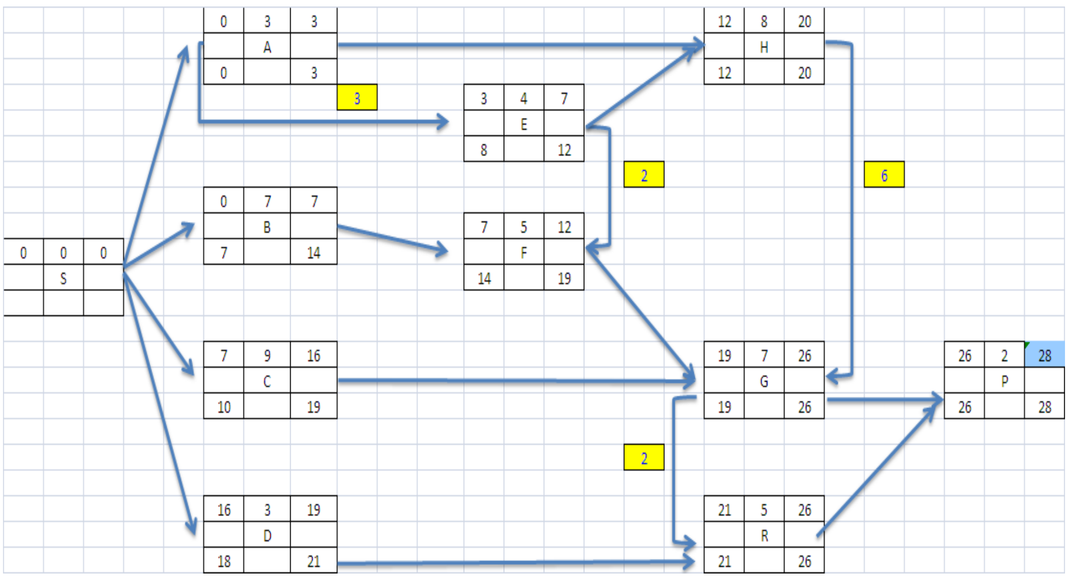

Figure 26. Network diagram after resource allocation using Flexible Scheduling

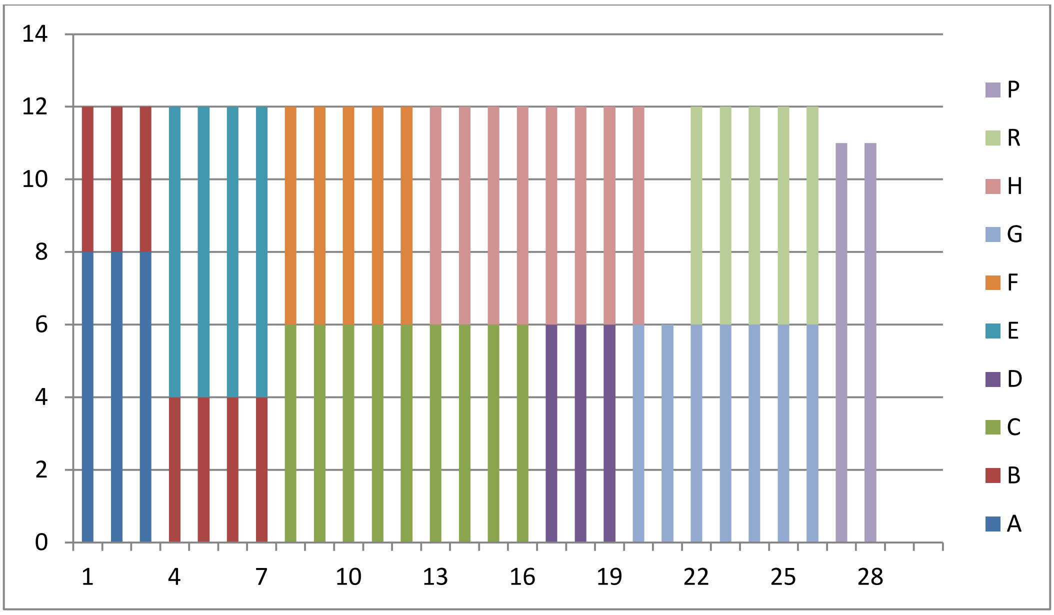

Figure 27. Histogram after resource allocation using Flexible Scheduling

The resulting schedule reflected 28 days duration (27% increment). Not only that, the overall project cost increased by 28% only. The flexible duration/resource could build-up in to a way better duration with less cost expenditure. The combination of scenarios, logic, and movement within float are as shown in Figures 28, 29 and 30.

Act	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
Za	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Zb	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Zc	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Zd	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Ze	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Zf	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Zg	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Zh	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Zr	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Zp	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Figure 28. Scenario selection after resource allocation using Flexible Scheduling

Act	ES	Const	As	Const	LS
A	0	=<=	0	=<=	0
B	0	=<=	0	<=	7
C	0	<=	7	<=	10
D	0	<=	16	<=	18
E	3	=<=	3	<=	8
F	7	=<=	7	<=	14
G	19	=<=	19	=<=	19
H	7	<=	12	=<=	12
R	21	=<=	21	=<=	21
P	26	=<=	26	=<=	26

Figure 29. Actual start times
(resource allocation using Flexible Scheduling)

Act	Res	Dur	OT	Cost
A	8	3	3	30000
B	4	7	1	26600
C	6	9	4	75600
D	6	3	3	22500
E	8	4	4	44800
F	6	5	1	28500
G	6	7	3	52500
H	6	8	3	60000
R	6	5	1	28500
P	11	2	1	20900

Figure 30. Activity attributes
(resource allocation using Flexible Scheduling)

A second run is required to examine the economical adequacy of the provided solution. Hence, the project duration was set to 28 days and the objective cell changed to minimizing total cost. The network diagram and the corresponding histogram are shown in Figure 31 and 32.

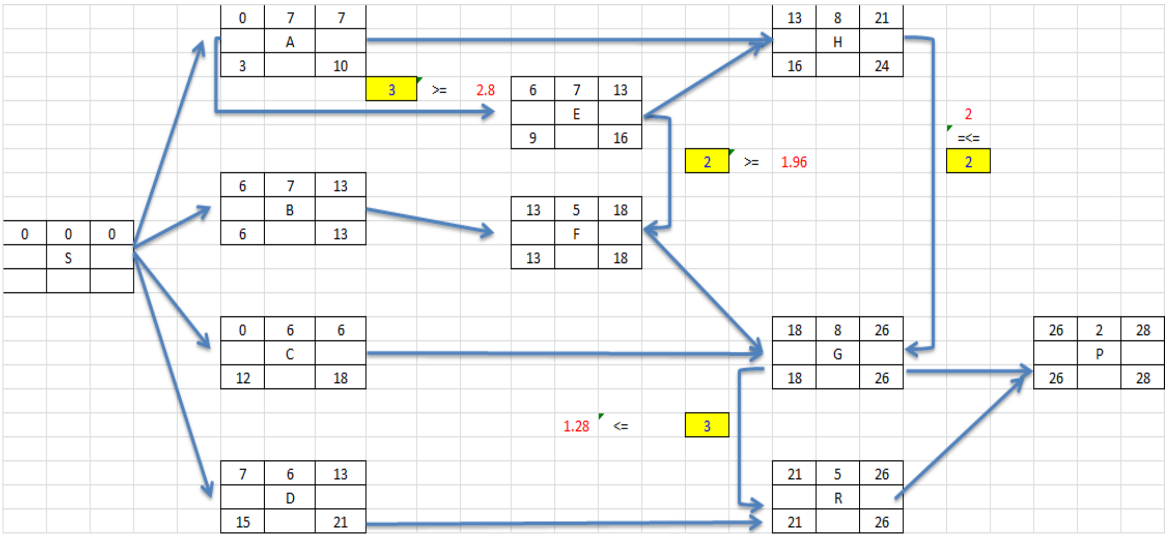

Figure 31. Network diagram after resource allocation using Flexible Scheduling (second run)

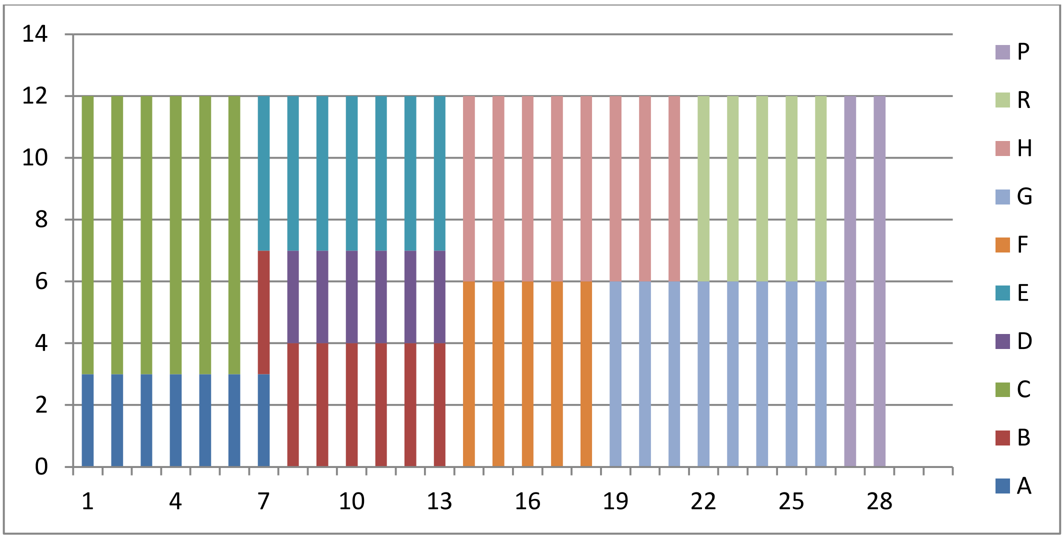

Figure 32. Histogram after resource allocation using Flexible Scheduling (second run)

Referring to Figures 33, 34 and 35, a better solution was found for resource allocation that reflected cheaper cost compared to the first objective run. The total cost dropped to $189,700. Not only that, the histogram further improved and reached to a perfectly leveled histogram. The cost inflated under the allocation constraint by about 19% (formerly 28%). Hence, the second run produced an absolute better solution in terms of how economic and how effective.

Act	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
Za	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Zb	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Zc	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Zd	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Ze	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zf	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Zg	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Zh	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Zr	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Zp	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 33. Scenario selection after resource allocation using Flexible Scheduling (second run)

Act	ES	Const	As	Const	LS
A	0	=<=	0	<=	3
B	0	<=	6	=<=	6
C	0	=<=	0	<=	12
D	0	<=	7	<=	15
E	3	<=	6	<=	9
F	13	=<=	13	=<=	13
G	18	=<=	18	=<=	18
H	13	=<=	13	<=	16
R	21	=<=	21	=<=	21
P	26	=<=	26	=<=	26

Figure 34. Actual start time (allocation with Flexible Scheduling – second run)

Act	Res	Dur	OT	Cost
A	3	7	4	10290
B	4	7	1	9310
C	9	6	4	26460
D	3	6	2	6930
E	5	7	0	9800
F	6	5	1	9975
G	6	8	0	13440
H	6	8	3	21000
R	6	5	1	9975
P	12	2	0	6720

Figure 35. Activity attributes (allocation with Flexible Scheduling – second run)

Again, all the scenarios chosen by the model as a solution were non-normal durations. In addition, the improvement that was imposed by Flexible Scheduling was significant and surpassed the classical allocation method. Flexible Scheduling outperformed classical method in terms of time and cost by widening the solution space and finding a better cheaper solution although overtime is an expensive option. In addition, fewer variations were present in the histogram which reflects a more stable project resource-wise.

A new cost trade-off was introduced by allowing for extra expenses of overtime and productivity losses in exchange of shorter duration and lesser cost under limited resource availability. The newly introduced approach successively produced a better, more feasible and more cost effective solution.

III. Project Crashing and Cost Optimization

The previously addressed objectives are extreme in the sense that an ideal solution of each objective is excessively costly. Although classical leveling costs nothing as a direct cost, it changes the risk status of the project due to the fact that all activities become critical and any delay will negatively affect the histogram. There are other imbedded costs such as float consumption cost or risk cost that are translated from probabilities to financial terms. Conversely, Flexible Scheduling manipulates expensive attributes such as overtime and produces productivity losses; both are expensive and might drain the project financially. However, the utilization of such manipulation extends the solution space and new optimum point might be achieved. Where some project managers prefer these extreme solutions, others would prefer to save up money and go with the cheapest combination.

Project crashing aims to shorten the project duration by shortening durations of critical activities. Usually, there are two outputs to time-cost trade-off problems – shortest duration & optimum duration. In the presence of liquidated damages, incentives and overhead (which all are function of time), the shortest duration might not be the cheapest and therefore an optimum duration midway between the current and the shortest exists. A comparison between classical project crashing and Flexible Scheduling is slightly inconsistent because of the difference in definition of crashing cost. On the other hand, Flexible Schedule is expected to provide better solution because it takes into consideration two extensions of time-cost trade off: all activities will be taken into consideration for crashing/relaxing and activities can be shortened or elongated.

In this research, an overall cost optimization is targeted such that a minimum cost will be achieved through different constraints. The output is expected to be detailed to the extent of providing what is the optimum resource assignment, working hours and starting time for each activity. Under cost optimization, different financial and resource constraints will be applied such as resource ceiling, or financial expenditure allocation. The following objective, variables, and constraints were imbedded into the model:

Objective Function:

$$\text{MIN } (C_T)$$

$$C_T = C_{HF} + C_{OH} + C_{LD} + (\sum_{i=1}^{n} C_{Li}) - I_n$$

Variables:

AS_i (Integer); Z_{mi} (Binary); L_{jin} (Integer)

Constraints:

$$ES_i \leq AS_i \leq LS_i;$$

$$L_{jin} \geq (\%comp\ constraint)\ x\ D_{jni}\ ;$$

$$\sum_{1}^{m} Z_{mi} = 1$$

In this particular objective, the project duration is free to extend or shorten as the goal of this practice is finding the optimum duration. After running the model, the results achieved were as shown in Figure 36 and 37.

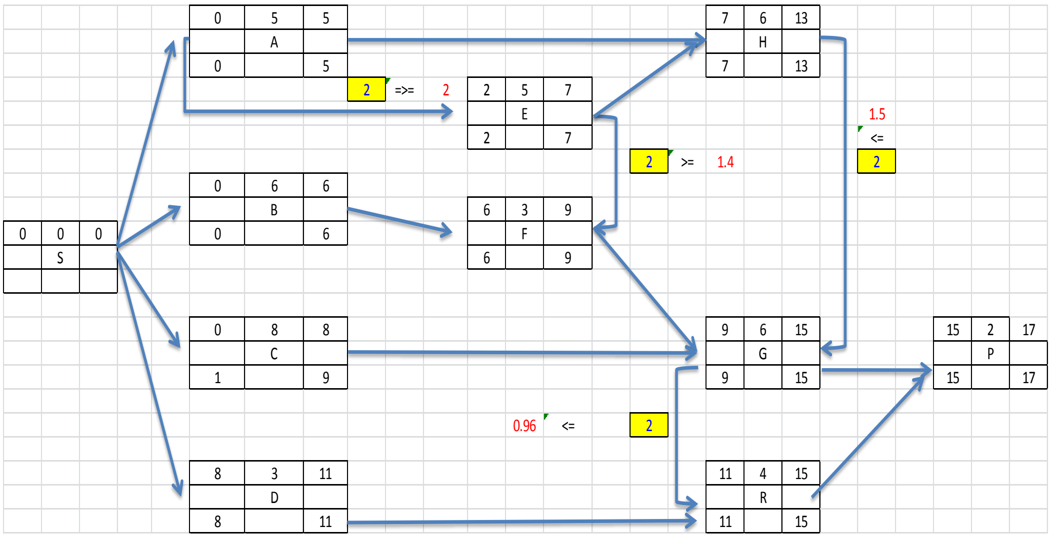

Figure 36. Network diagram after cost optimization using Flexible Scheduling

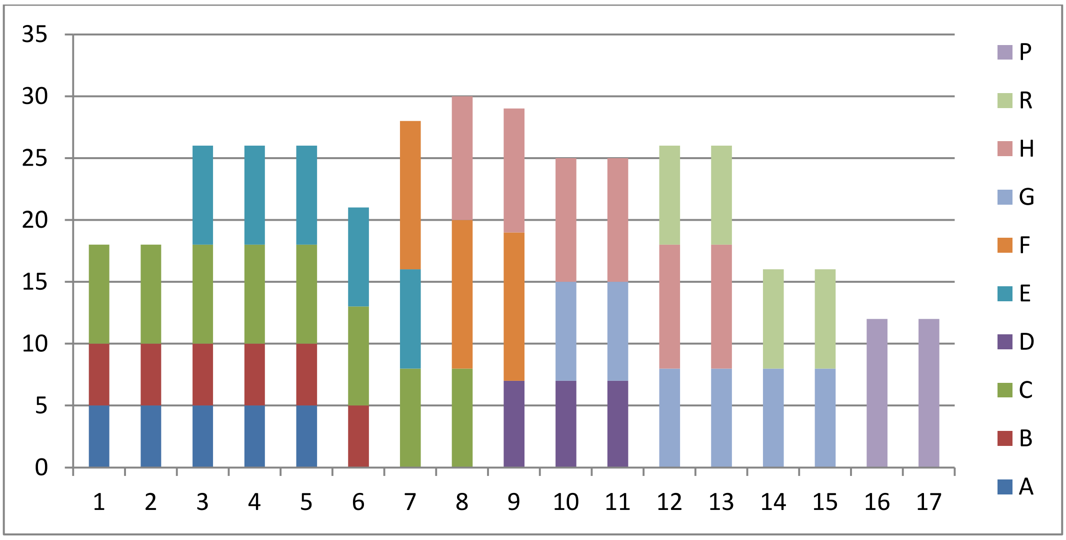

Figure 37. Histogram after cost optimization using Flexible Scheduling

Act	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
Za	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zb	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zc	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zd	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Ze	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Zf	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Zg	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zh	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Zr	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zp	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 38. Scenario selection after cost optimization using Flexible Scheduling

Act	ES	Const	As	Const	LS
A	0	=<=	0	=<=	0
B	0	=<=	0	=<=	0
C	0	=<=	0	<=	1
D	0	<=	8	=<=	8
E	2	=<=	2	=<=	2
F	6	=<=	6	=<=	6
G	9	=<=	9	=<=	9
H	7	=<=	7	=<=	7
R	11	=<=	11	=<=	11
P	15	=<=	15	=<=	15

Figure 39. Actual start times
(cost optimization using Flexible Scheduling)

Act	Res	Dur	OT	Cost
A	5	5	0	7000
B	5	6	0	8400
C	8	8	0	17920
D	7	3	0	5880
E	8	5	0	11200
F	12	3	0	10080
G	8	6	0	13440
H	10	6	0	16800
R	8	4	0	8960
P	12	2	0	6720
	Labor Cost			106400
	O/H			34000
	Liquidated Damages			-3000
	Hiring/Firing			6300
	Total Cost			143700
	Initial Cost			159340

Figure 40. Activity attributes
(cost optimization using Flexible Scheduling)

The overall cost reduced by 9.8% corresponding to an optimum duration of 17 days, maximum demand of 30 workers, hiring/firing counts of 42 practices and a mixture of normal and newly introduced scenario. It is noticeable that none of extreme objectives, leveling and allocation, dominated as the best solution of the network in terms of cost.

Indeed, this optimum solution is subject to the problem parameters and inputs. For example, if the overtime was set to 1.25 of the regular pay, like in the UAE, there is a chance that a different combination would result in the optimum solution. This can be noticed from the modeling results where no scenario that includes overtime was chosen (Figure 40). Therefore, the same last objective was run by changing the overtime pay to 1.25 of the labor hourly charge. The results obtained reflected overtime utilization in scenarios. This indicates that the choice of overtimes depends on the project parameter such as overtime cost. The results were as shown in Figures 41, 42, 43 and 44.

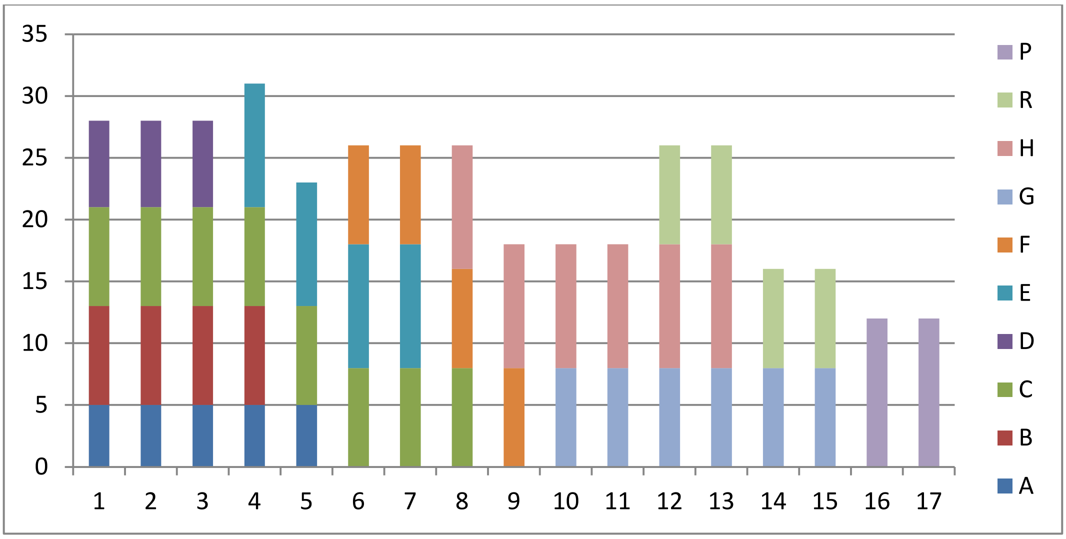

Figure 41. Histogram after cost optimization using Flexible Scheduling and overtime pay rate of 1.25

Referring to Figures 42, 43 and 44, the results reflected choices of scenarios that include minimal overtime. This reflected that a new optimum point was achieved corresponding to 17 days duration, 41 hiring-firing count, and peak demand on 31 days. Also, the cost dropped from $159,340 to $146,590 dropping by 8%. However, there is no trace of relaxation scenarios due to the fact that overhead and incentives overruled overtime in terms of cost and consequently no duration expansion was found to be optimum.

Act	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
Za	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zb	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Zc	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zd	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Ze	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Zf	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zg	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zh	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Zr	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zp	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 42. Scenario selection after cost optimization using Flexible Scheduling and overtime pay rate of 1.25

Act	ES	Const	As	Const	LS
A	0	=<=	0	<=	1
B	0	=<=	0	<=	1
C	0	=<=	0	<=	1
D	0	=<=	0	<=	8
E	2	<=	3	=<=	3
F	5	=<=	5	=<=	5
G	9	=<=	9	=<=	9
H	7	=<=	7	=<=	7
R	11	=<=	11	=<=	11
P	15	=<=	15	=<=	15

Figure 43. Actual start times
(cost optimization and overtime pay rate of 1.25)

Act	Res	Dur	OT	Cost
A	5	5	0	7000
B	8	4	1	10360
C	8	8	0	17920
D	7	3	0	5880
E	10	4	1	12950
F	8	4	0	8960
G	8	6	0	13440
H	10	6	0	16800
R	8	4	0	8960
P	12	2	0	6720
	Labor Cost			108990
	O/H			34000
	Liquidated Damages			-3000
	Hiring/Firing			6600
	Total Cost			146590
	Initial Cost			144790

Figure 44. Activity attribute
(cost optimization and overtime pay rate of 1.25)

IV. Cost Optimization and Resource Allocation

Because overhead, incentives, liquidated damages, and labor cost dominated over hiring-firing cost, and because there is no cost translation of peak demand, cost optimization results isolated variation in the histogram and maximum demand over the project life cycle. Hence, as a new constraint, a resource availability ceiling (RC) will be added to the cost optimization model such that the model is set to find the minimum cost given this ceiling. The results were as shown in Figures 45 to 49.

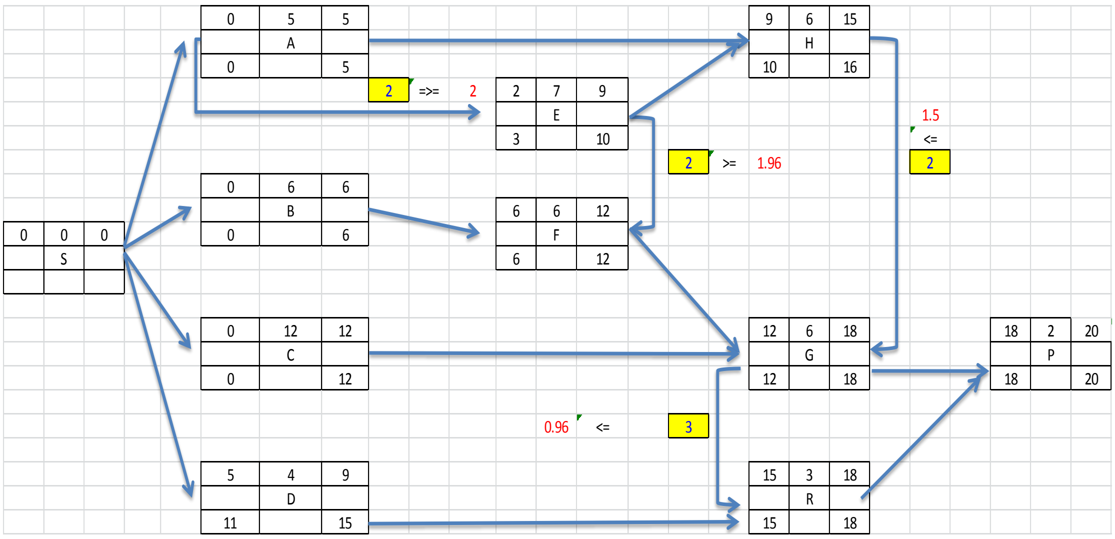

Figure 45. Network diagram after cost optimization and resource allocation using Flexible Scheduling

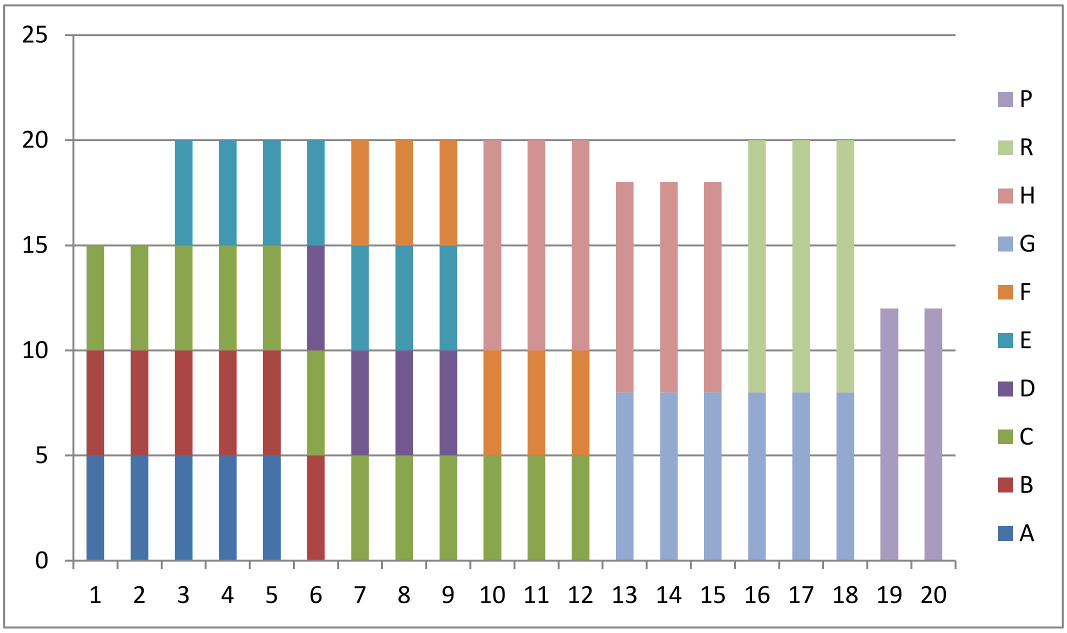

Figure 46. Histogram after cost optimization and resource allocation using Flexible Scheduling

Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 47. Scenarios selection after cost optimization and resource allocation using Flexible Scheduling

Act	Res	Dur	OT	Cost
A	5	5	0	7000
B	5	6	0	8400
C	5	12	1	19950
D	5	4	0	5600
E	5	7	0	9800
F	5	6	1	9975
G	8	6	0	13440
H	10	6	0	16800
R	12	3	0	10080
P	12	2	0	6720
	Labor Cost			107765
	O/H			40000
	Liquidated Damages			0
	Hiring/Firing			2550
	Total Cost			150315
	Initial Cost			159340

Figure 48. Actual start times
(cost optimization and resource allocation)

Act	ES	Const	As	Const	LS
A	0	=<=	0	=<=	0
B	0	=<=	0	=<=	0
C	0	=<=	0	=<=	0
D	0	<=	5	<=	11
E	2	=<=	2	<=	3
F	6	=<=	6	=<=	6
G	12	=<=	12	=<=	12
H	9	=<=	9	<=	10
R	15	=<=	15	=<=	15
P	18	=<=	18	=<=	18

Figure 49. Activity attributes
(cost optimization and resource allocation)

The final solution indicates that, under the given constraints, the optimum duration is 20 days (same as contractual duration), peak demand of 20, hiring-firing count of 17 practices, and cost of $150,315 (reduced by 5.7%). In addition, the solution used the new contributions of the research – relaxation, crashing non-critical activities, and overtime. Relaxation was done on activity C, crashing non-critical activity was performed on activity H, and overtime was indicated in activities C and F. Besides, the optimum start date was found for each activity. Under these particular objectives (cost optimization combined with allocation), Flexible Scheduling has examined more options in achieving optimum solution that other classical methods would not examine.

3.5.3 Discussion of Results

Table 5 summarizes the results obtained from all Flexible Scheduling models.

Table 5
Summary of Results

Attributes	Duration	Peak demand	Hiring-firing	Cost
CPM	22	28	78	159340
Classical Allocation	42	12	18	211390
Flexible Scheduling Allocation	28	12	0	189700

Attributes	Duration	Peak demand	Hiring-firing	Cost
CPM	22	28	78	159340
Classical Leveling	22	23	40	153640
Flexible Scheduling Leveling	22	15	3	183685

Attributes	Duration	Peak demand	Hiring-firing	Cost
CPM	22	28	78	159340
Cost Optimization	17	30	42	143700
Cost Optimization + Allocation	20	20	17	150315

The model successfully implemented all targeted flexibility in resources, duration, and logic between activities. After pre-determination of scenarios and inserting them into the model as discrete values, different constraints are set to assure feasibility and consistency with the different objectives. The traditional objectives of resource leveling, resource allocation and cost optimization are examined in addition to further constrained objectives such as cost optimization under resource limited availability.

Flexible Scheduling has demonstrated excellent abilities to serve extreme objectives such as leveling and allocation. It also outperformed current classical method of achieving these extreme objectives by distinguishably better readings. However, because Flexible Scheduling allows manipulation through overtime rate (1.5 regular pay), there were cost increments accompanying the almost-ideal solutions. Hence, Flexible Scheduling presented a new cost tradeoff between efficiency-overtime and leveling. Nevertheless, all of the newly introduced flexibilities were utilized in the cost optimization under limited resource availability; therefore, if other traditional techniques were to solve for the same objective, the solution might be infeasible or at least less optimum.

One of the challenges about the software *What'sBest* was the limitation to one objective cell. This affects the model results in the sense that when minimizing a technical aspect of the project (variations or duration), there might exist several combinations of scenarios that serve the desirable result. Hence, after finding the best solution for the technical attribute, a second is conducted targeting minimizing the cost with a newly added constraint of fixing the technical attributes to its minimum found solution.

The newly introduced scheduling technique presented better results overall for all objectives and distinguishably in extreme and special objectives. In addition, the provided solution is detailed enough to tell what is the best number of workers to be assigned to each activity, for how many hours should workers work in each activity, and when is the best time to start non-critical activities. Also, the approach strongly assists in decision making by introducing new trade-offs between efficiencies and desired objective.

CHAPTER 4: VALIDATION

4.1 Introduction

CPM does not inspect resource attributes in the network and therefore CPM's solution might not be feasible or optimum. Hence relating resources (histogram) to the network helped improving the integrity of the network and therefore coming up with feasible solutions. In addition, allowing each activity to change in terms of duration, resource, and working hours helped explore more options to solve/optimize project-related problems. This chapter aims to compare previous works from literature to the approach of this research. This comparison is meant to examine Flexible Scheduling ability, as an approach, to achieve better results in both cases of extreme and optimal objectives. In addition, the ability of *What'sBest* will be examined by solving several problems and comparing the results to the ones found in previous literature. The flexibility granted to the network by using Flexible Scheduling allowed for more constraints and special objectives which will also be presented in this chapter through a hypothetical example.

For each example, the objective will be achieved using both classical methods and Flexible Scheduling. Cost will also be demonstrated to reflect the cost increments associated with Flexible Scheduling that result from productivity losses and overtime cost.

In this research, four objectives were examined:

1. Resource Leveling

   This objective aims to minimize fluctuations in the histogram. Traditionally, enhancements in the histogram would be achieved through movements within available float with restriction on the duration.

2. Resource Allocation

   Resource allocation is used when there is a limited availability of resources and therefore, there is a need to reschedule each activity such that the resource ceiling is not violated. This practice usually leads to time extension.

3. Resource Leveling and Allocation

This is a newly introduced objective that assumes resource ceiling and aims to minimize the variations. This objective serves best those who hire a constant number of workers (at the maximum demand) and want to avoid idle time for workers; therefore the objective would be set to finding a leveled histogram given a certain resource limitation.

4. Cost Optimization

The main cost attributes that are taken into consideration in this research are: labor cost, hiring/firing cost, overhead, liquidated damages, and lncentives of early finish. Traditionally, total cost is reduced through stand-alone enhancements such as resource leveling (minimum hiring-firing), liquidated damages and incentives (project crashing). On the other hand, labor costs are supposed to increase when performing crashing which leads to the conclusion that the shortest duration might not correspond to the lowest cost. In addition, usually project crashing focuses on the cost increments and ignores the mess-ups resulting in the histogram due to resource hiring and/or increasing working hours.

Flexible Scheduling is an extended case of project crashing and cannot be compared against because of the argument on crashing cost. However, Flexible Scheduling takes into consideration crashing all activities including non-critical activities, activity relaxation and resource leveling. Thus, all activities will be allowed to:

- Crash in duration ↔ Increase resources and/or working hours.
- Relax duration ↔ Decrease resources.
- Move within available float.

4.2 Resource Leveling

The following network was extracted from Doulabi et al. [**31**]

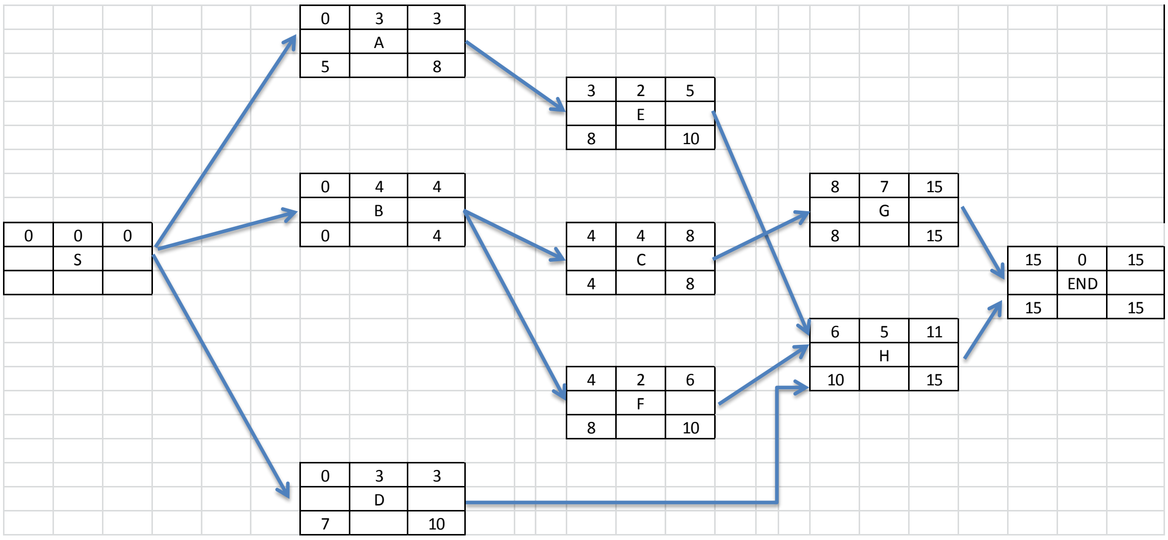

Figure 50. Initial network diagram (Example 1)

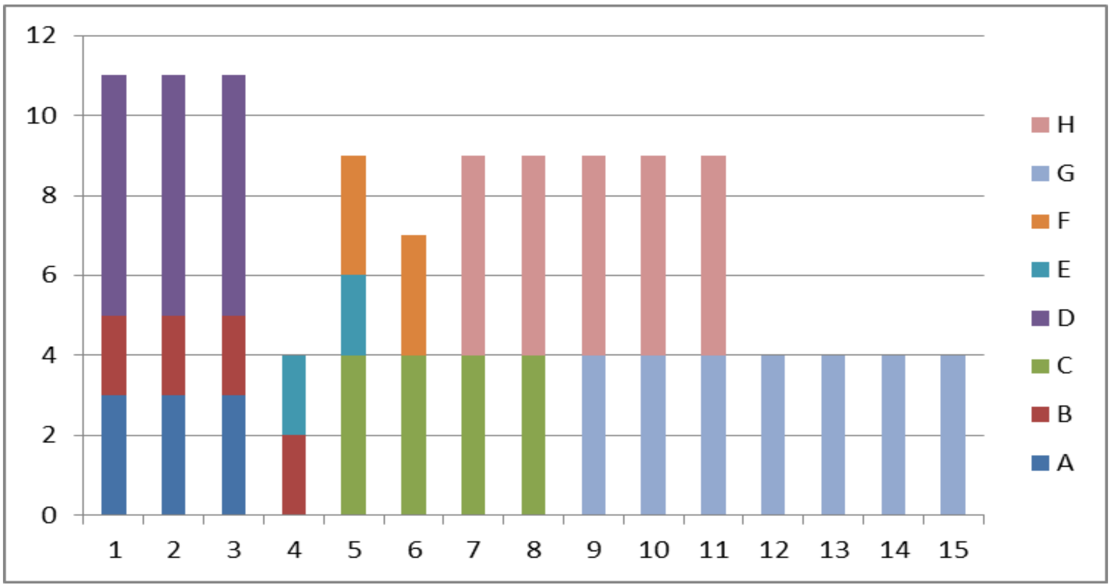

Figure 51. Initial histogram (Example 1)

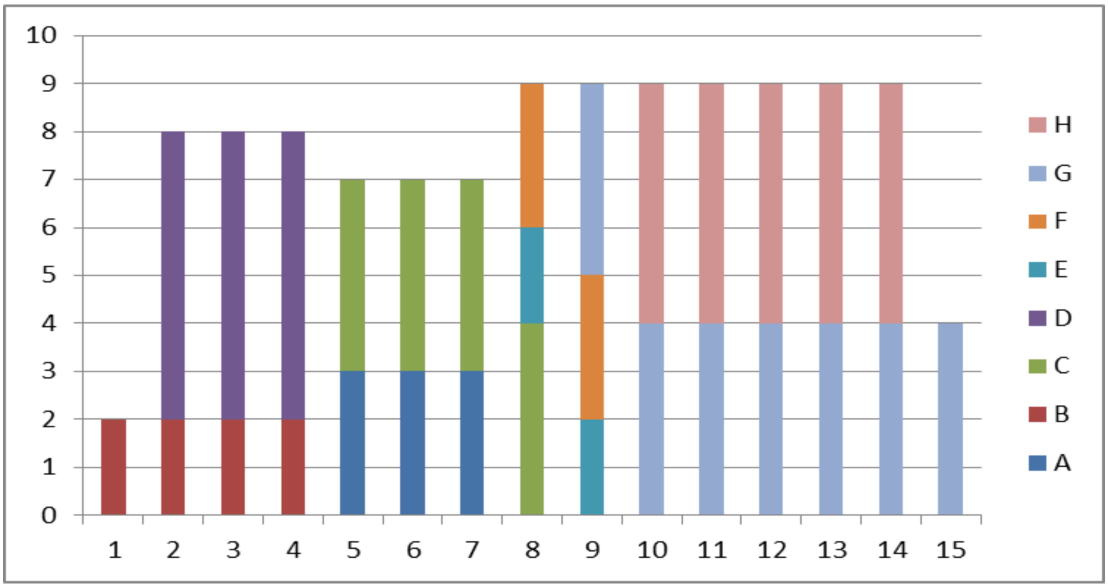

Figure 52. Leveled histogram (traditional method - movement within float)

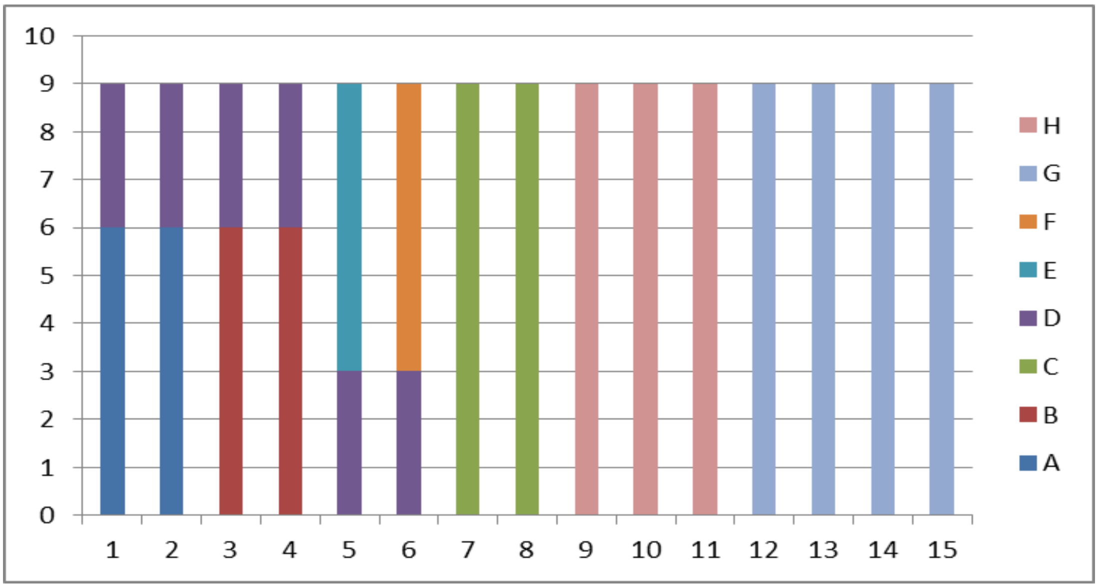

Figure 53. Leveled histogram (Flexible Scheduling)

Act	ES	Const	As	Const	LS
A	0	=<=	0	<=	9
B	0	<=	2	<=	7
C	4	<=	6	<=	9
D	0	=<=	0	<=	6
E	2	<=	4	<=	11
F	4	<=	5	<=	11
G	8	<=	11	=<=	11
H	6	<=	8	<=	12

Figure 54. Activity start times
(Flexible Scheduling leveling)

	Res	Dur	OT	Cost
A	6	2	0	3360
B	6	2	0	3360
C	6	3	0	5040
D	3	6	0	5040
E	6	1	0	1680
F	3	2	0	1680
G	9	4	0	10080
H	9	3	1	8977.5

Figure 55. Activity attributes
(Flexible Scheduling leveling)

Table 6

Resource Leveling Results Summary and Comparison

Scheduling Technique	Hiring/firing count	Maximum resource requirement	Cost increment in labor cost
Original	21	11	0%
Traditional	14	9	0%
Flexible	0	9	22.9%

Using Flexible Scheduling, a completely leveled histogram was achieved at 23% labor cost increment (not including other costs such as overhead, hiring firing cost…etc). In addition, the maximum peak demand dropped from 11 workers to 9. This schedule represents complete utilization of the resource at one constant hiring level. On the other hand, traditional leveling only achieved 7 hiring-firing practices (from 21 to 14) with no cost increments.

4.3 Resource Allocation

This example was extracted from Zhang et al. [**32**]

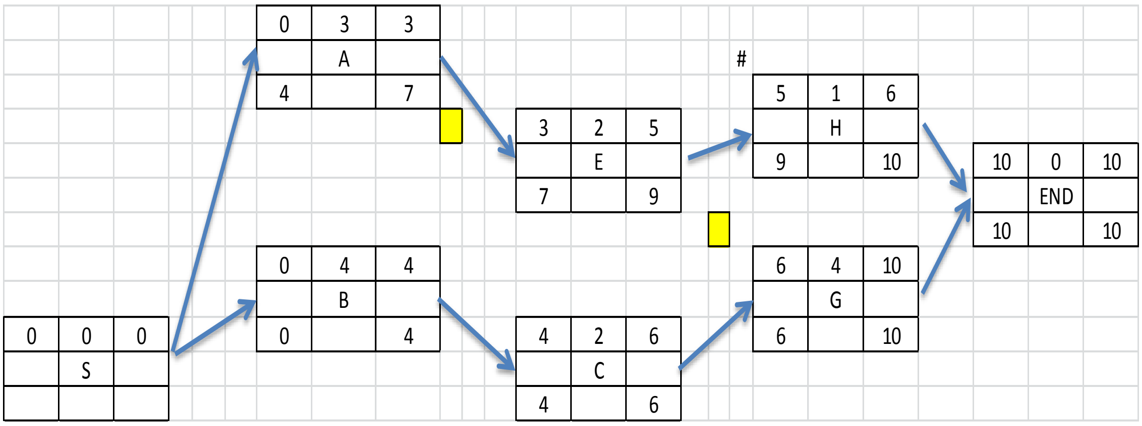

Figure 56. Initial network diagram (Example 2)

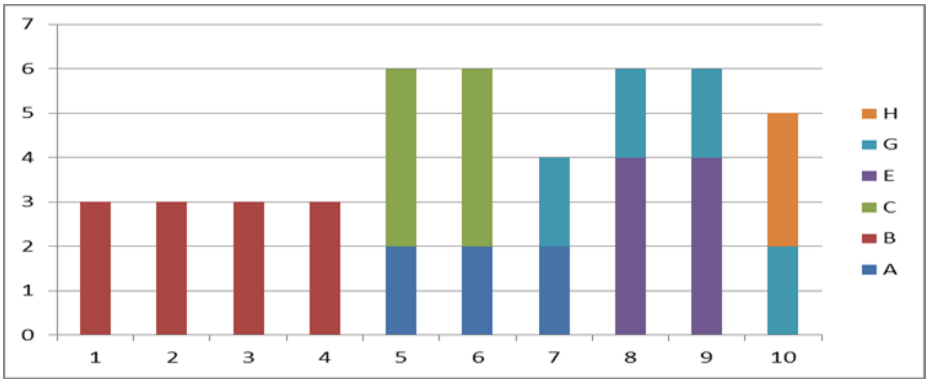

Figure 57. Initial histogram (Example 2)

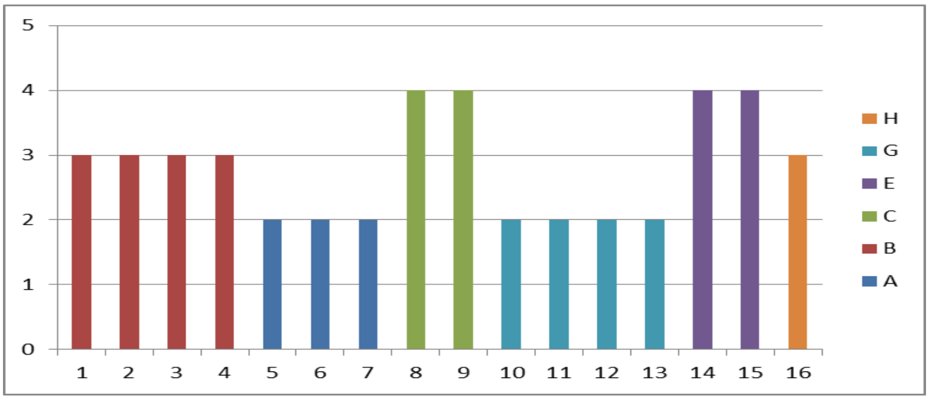

Figure 58. Traditional allocation histogram (Example 2) – resource limitation = 4

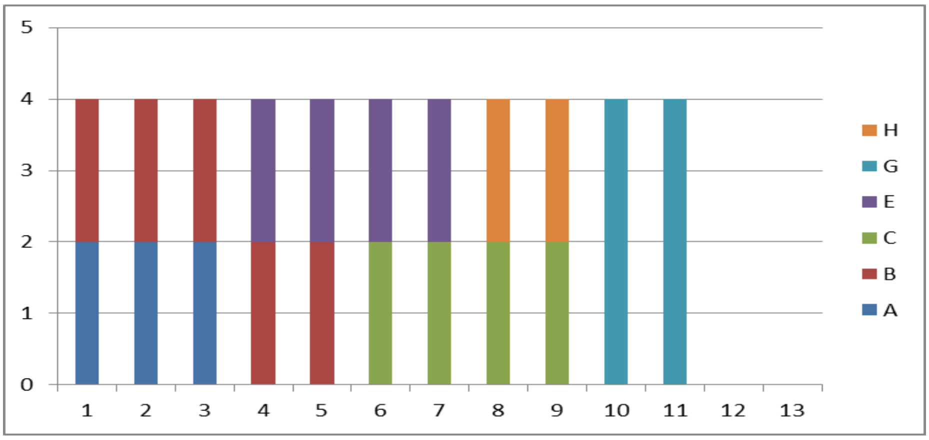

Figure 59. Flexible Scheduling allocation histogram (Example 2) – resource limitation = 4

Act	ES	Const	As	Const	LS
A	0	=<=	0	<=	2
B	0	=<=	0	=<=	0
C	5	=<=	5	=<=	5
E	3	=<=	3	<=	5
G	9	=<=	9	=<=	9
H	7	=<=	7	<=	9

Figure 60. Activity start times
(Flexible Scheduling allocation)

	Res	Dur	OT	Cost
A	2	3	0	1680
B	2	5	4	4900
C	2	4	0	2240
E	2	4	0	2240
G	4	2	3	3500
H	2	2	3	1750

Figure 61. Activity attributes
(Flexible Scheduling allocation)

Table 7
Resource Allocation Results Summary and Comparison

Scheduling Technique	Hiring/firing count	Maximum resource requirement	Duration	Cost increment in labor cost
Original	9	8	10	0%
Traditional	8	4	14	0%
Flexible	0	4	11	29.4%

Flexible Scheduling produced significantly better solution for resource allocation of the given example. The duration only increased by 1 day (10%) whereas using traditional technique the resulting duration was 14 days (40% increment). Not only that, smoother histogram was achieved. Variations dropped by one using traditional technique whereas completely eliminated using Flexible Scheduling. This enhancement came at a labor cost increment of 30% (assuming 1.5 pay rates for overtime). These enhancements can offer savings in other attributes of the projects such as hiring-firing, liquidated damages/incentives and overhead costs.

4.4 Cost Optimization

Due to the absence of an example that provides all the cost attributes, this hypothetical example was constructed to further demonstrate abilities and advantages of Flexible Scheduling in the cost optimization objective.

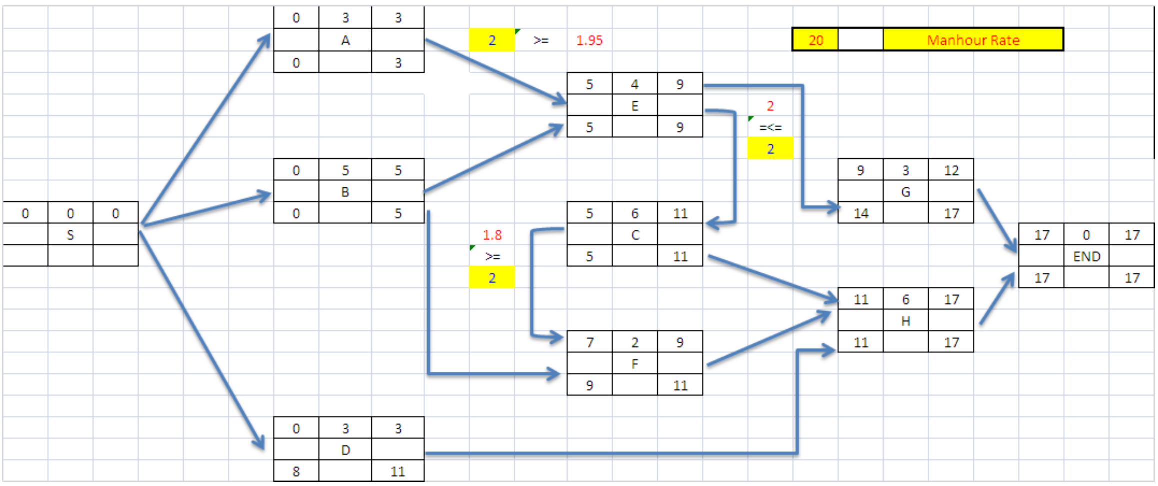

Figure 62. Initial CPM network diagram (Example 3)

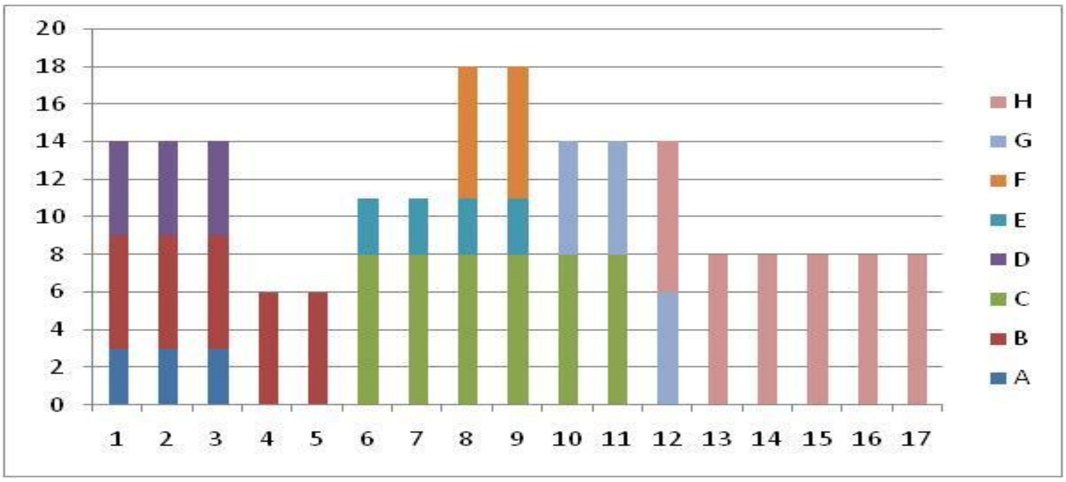

Figure 63. Initial CPM histogram (Example 3)

Initial cost of the project including labor, overhead, hiring-firing, liquidated damages/incentives resulted in $49,140. Initially, using CPM, there were 30 hiring-firing practices, 3 days extension beyond contractual date (14 days) and overhead of $13,600. In addition, the maximum demand was 18 workers peaking at days 8 & 9.

		Res	Dur	OT	Cost
	A	3	3	0	1440
	B	6	5	0	4800
	C	8	6	0	7680
	D	5	3	0	2400
	E	3	4	0	1920
	F	7	2	0	2240
	G	6	3	0	2880
unit	H	8	6	0	7680
800	OH				13600
150	Hiring-Firing				4500
1000	Liquidated Damages				3000
	Total Cost				49140

Figure 64. Attributes summary

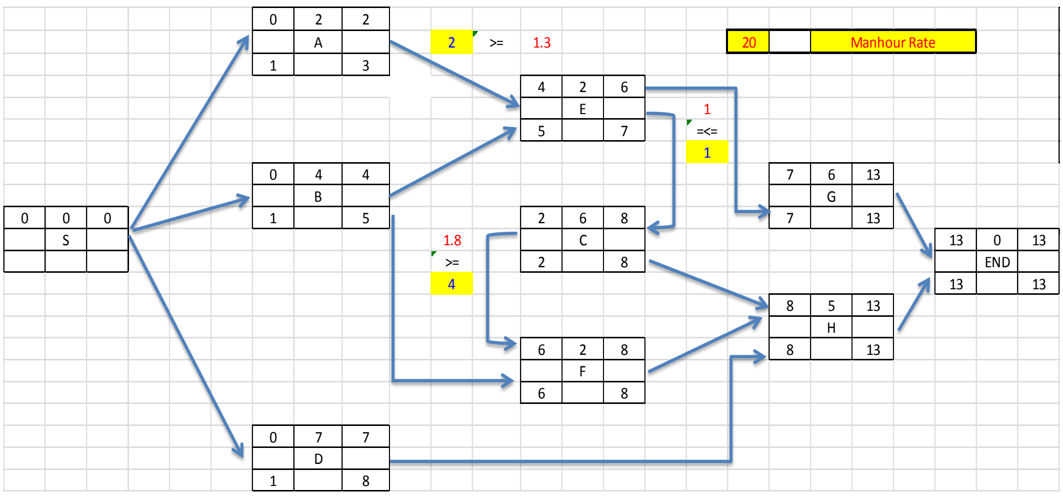

Figure 65. Adjusted network diagram – optimum cost using Flexible Scheduling (Example 3)

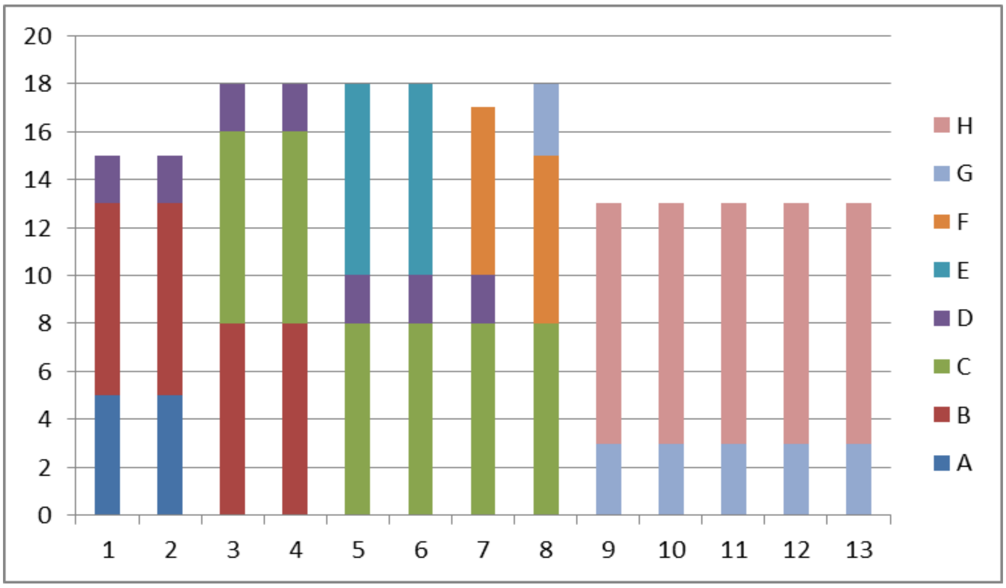

Figure 66. Adjusted histogram – optimum cost using Flexible Scheduling (Example 3)

		Res	Dur	OT	Cost
	A	5	2	0	1600
	B	8	4	0	5120
	C	8	6	0	7680
	D	2	7	0	2240
	E	8	2	0	2560
	F	7	2	0	2240
	G	3	6	0	2880
unit	H	10	5	0	8000
800	OH				10400
150	Hiring-Firing				1500
1000	Liquidated Damages				-1000
	Total Cost				44220

Figure 67. Attributes summary – optimum cost using Flexible Scheduling

After running the model using Flexible Scheduling attributes, the cost reduced to $44,220 (by 10%) (Figure 67) and the duration corresponded to 13 days (Figure 66). The model traded off among all attributes that contributed to the project total cost. The resulting schedule was midway in terms of variations, liquidated damages, and overhead. Any change of any attribute is expected to reflect higher price. However, the maximum demand remained the same at 18 workers which might conflict with, if exists, a resource availability limitation.

4.5 Cost Optimization with Allocation

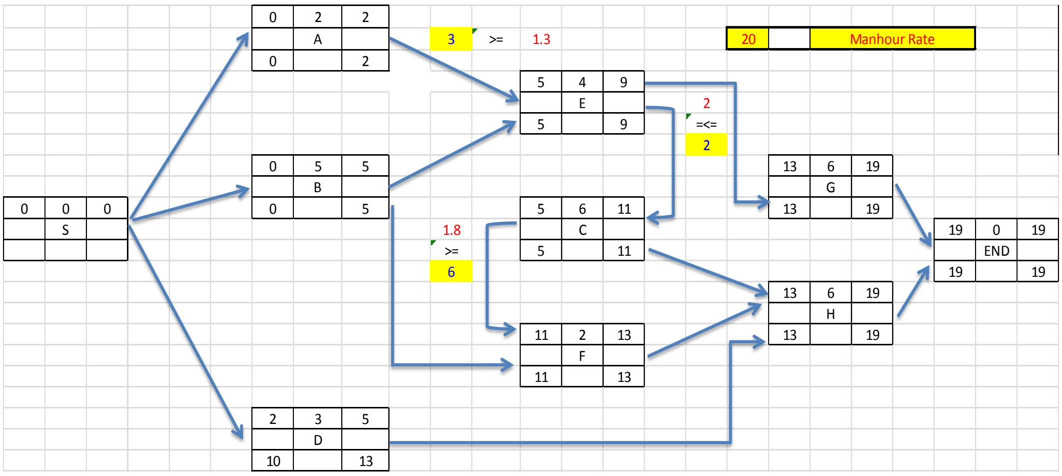

Figure 68. Network diagram – cost optimization with resource allocation (Example 4)

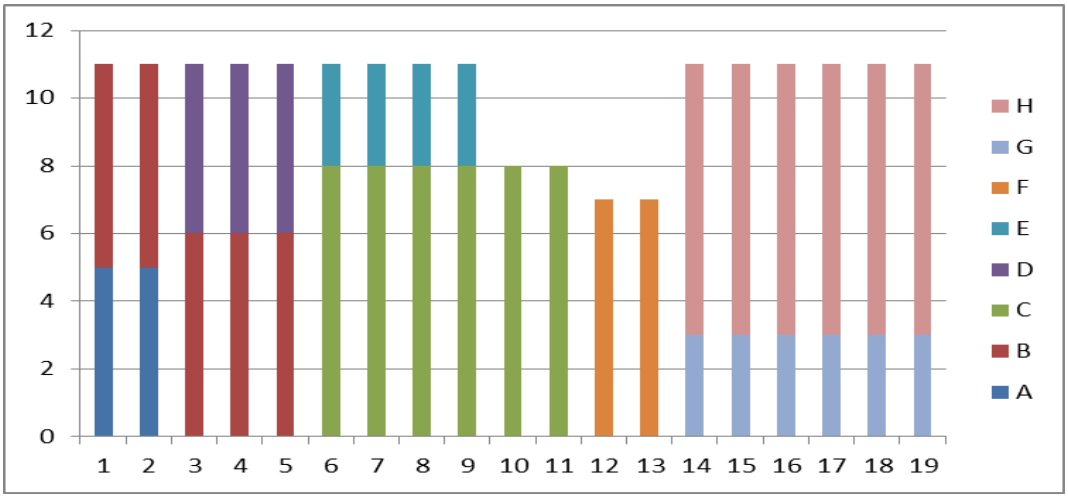

Figure 69. Resource histogram – cost optimization with resource allocation (Example 4)

		Res	Dur	OT	Cost
	A	5	2	0	1600
	B	6	5	0	4800
	C	8	6	0	7680
	D	5	3	0	2400
	E	3	4	0	1920
	F	7	2	0	2240
	G	3	6	0	2880
unit	H	8	6	0	7680
800	OH				15200
150	Hiring-Firing				1200
1000	Liquidated Damages				5000
	Total Cost				52600

Figure 70. Attributes summary – cost optimization with resource allocation

The schedule resulted in 19 days, and total cost of $52,600 (Figure 69 and 70). The minimum cost was achieved by balancing all cost, time-related, and resource based attributes. Although the cost was higher than the CPM cost, less number of workers now is needed and hence all constraints were satisfied. Further adjustments might better enhance the histogram in terms of variations or peak demand; however, the resulting cost is expected to increase accordingly.

4.6 Reducing Maximum Demand

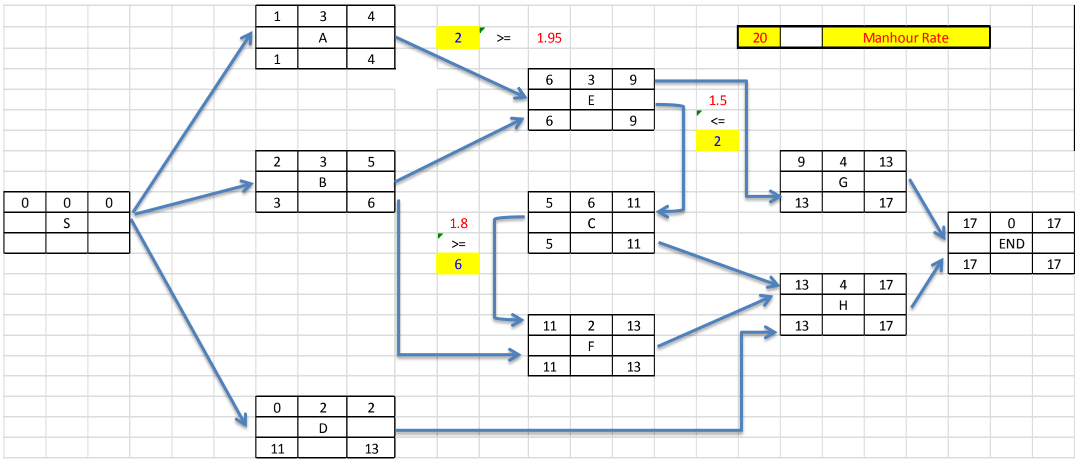

Figure 71. Network diagram – reducing maximum demand (Example 5)

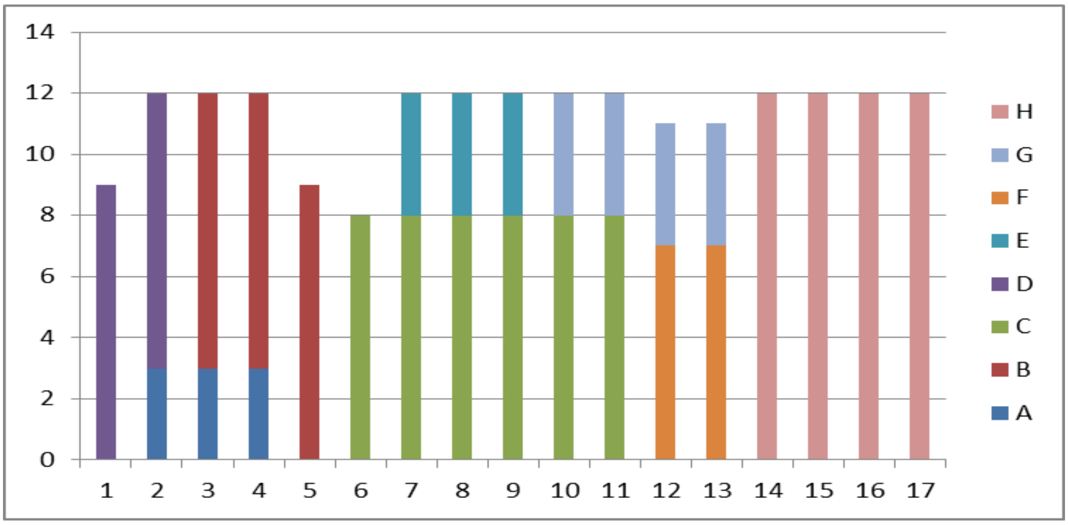

Figure 72. Resource histogram – reducing maximum demand (Example 5)

		Res	Dur	OT	Cost
	A	3	3	0	1440
	B	9	3	4	7560
	C	8	6	0	7680
	D	9	2	0	2880
	E	4	3	1	2280
	F	7	2	0	2240
	G	4	4	2	3520
unit	H	12	4	1	9120
800	OH				13600
150	Hiring-Firing				1950
1000	Liquidated Damages				3000
	Total Cost				55270

Figure 73. Attributes summary – reducing maximum demand

This objective served as a middle way between resource leveling and resource allocation; it aimed to find the minimum maximum number of workers for this particular project given the same project duration. The result of this particular example was 12 workers at max per day would be sufficient if scheduled according to the given attributes. Resulting cost were higher; however, smoother and less aggressive histogram resulted.

4.7 Validation of *What'sBest*

This example is constructed by El-Rayed and Jun [**20**]. The aim of demonstrating this example is not to examine Flexible Scheduling, but rather examine the software *What'sBest* in achieving results of different objectives under different constraints. In the research, two separate objectives were targeted: reduce the maximum demand and minimize the absolute differences.

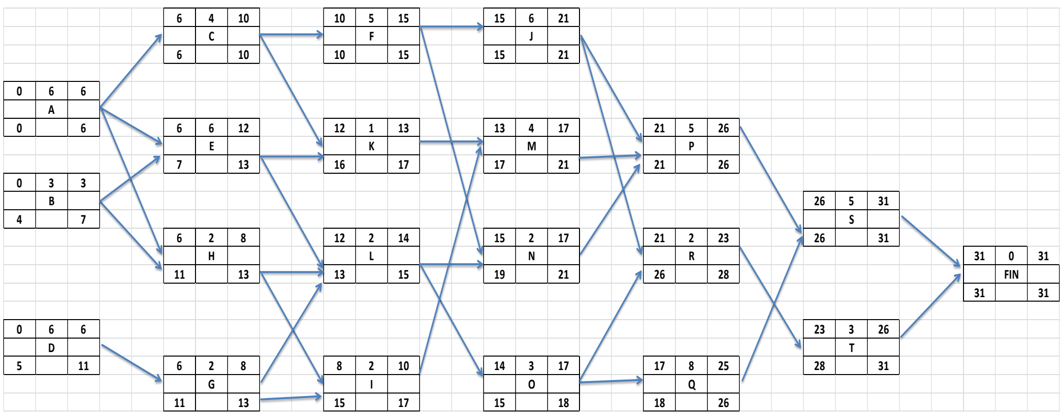

Figure 74. Network diagram according to [20]

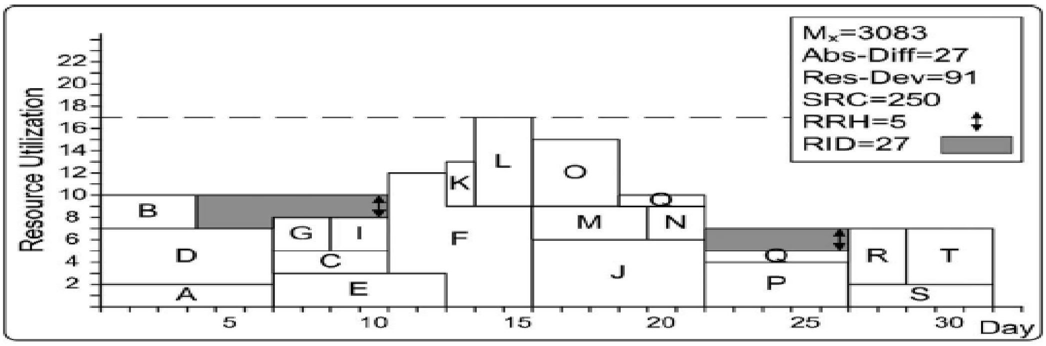

Figure 75. Resource histogram according to [20]

The problem was modeled in Excel and run by *What'sBest* with results as shown in Figure 76 and 77. The results achieved by *What'sBest* were similar to the research results. The maximum demand reduced from 21 to 17 and the absolute differences in resource utilizations dropped from 42 to 27.

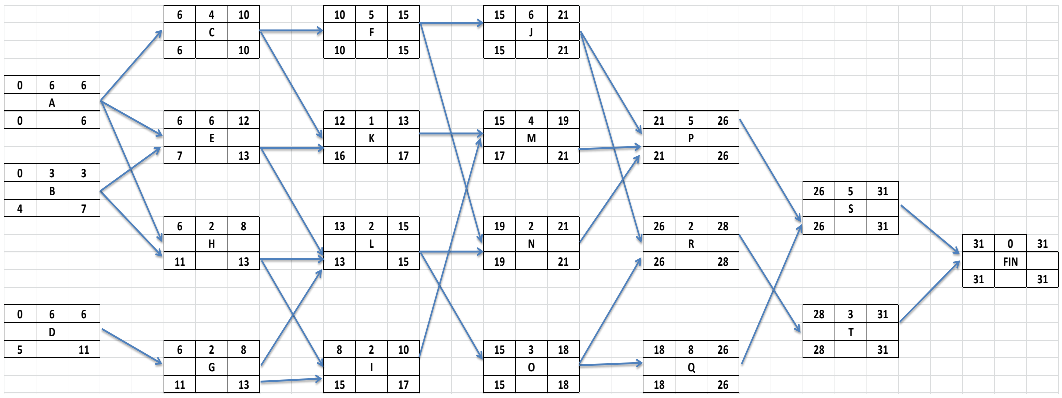

Figure 76. Network diagram according to *What'sBest* results

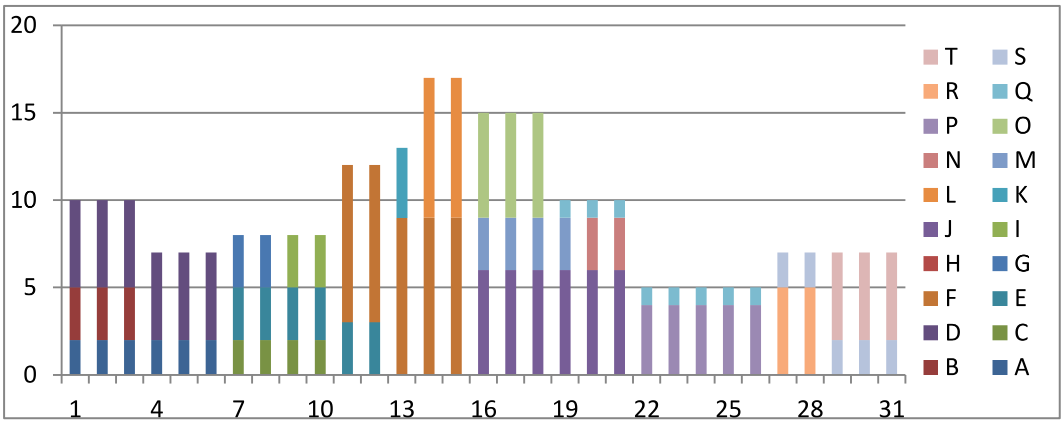

Figure 77. Network diagram according to *What'sBest* results

- Solution Optimality

Flexible Scheduling model has a nonlinear structure as it contains Excel logic functions such as IF, AND, MAX, MIN…etc. Not only that, the model contains integer variables bounded by functions when determining the actual starting time in order to assure consistency of the solution.

What'sBest uses a global solver to find the global optimum solution for nonlinear models. In the absence of a mathematical proof to a globally optimum solution for nonlinear model, global solver utilized a computationally proved approach in generating the global optimum solution for nonlinear problem. According to Gau & Scharge, [**33**], the global solver is based on the following ideas:

- Breaking down non-convex problem into several convex sub-problems.
- Utilization of Convex, Interval, and Algebraic (CIA) analysis.
- Enhanced branch-and-bound technique is intensively used to search a mathematically proved solution for the convex sub-problems.

Global Solver keeps breaking down sub-problems until reaching a purely convex sub-problem with a consistent bounding function and then solves them separately. The steps of this approach includes breaking down, validating bounding function and branching, breaking further if needed, and solving each sub-problem separately. The approach was implemented on 55 nonlinear models and successfully obtained the global optimum solution for all of them. However, a significant increase on solving time has been noticed [33]

Hence, the solutions provided by *What'sBest* are computationally proven to be the global optimum solutions.

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

A new scheduling technique called Flexible Scheduling is developed. The new model provides improved results when compared to current existing scheduling techniques. The new model introduces new flexibilities into construction schedules in terms of duration, resource assignment, working hours and applicable lags. Using Flexible Scheduling, each activity is allowed to experience different scenarios of workers' assignment and working hours. Consequences of resource variability, such as applicable lags between activities and associated productivity losses, are taken into consideration in the modeling. This means that each activity could, regardless of it criticality, have longer or shorter duration than the normal one based on the selected scenario. This newly-added flexibility to CPM helps overcome its rigidity and other shortcomings like isolation from resource constraints.

The model is constructed in Excel and the optimization software is an Excel add-in called *What'sBest*, which has the capability to solve nonlinear models. The process of creating a Flexible Scheduling model is divided into two separate sub-processes in order to allow adjustments and to ensure feasibility of the solution. The first sub-process is to come up with all possible scenarios the activities. The second sub-process includes defining and running the model. The main three objectives examined under Flexible Scheduling are resource leveling, resource allocation and cost optimization.

Comparing the results achieved by implementing Flexible Scheduling against current scheduling techniques has shown significant improvements. Resource leveling and resource allocation histograms are smoother and more adequate than the ones obtained by current techniques at a marginal additional cost. Therefore, Flexible Scheduling could achieve a tri-polar trade-off between time, cost, and efficiency. In other words, other potential solutions are found with better extreme objectives such as leveling and allocation. The resulting schedule introduced a new cost for leveling such that a further leveled histogram can be attained at an extra cost. In regards to resource allocation, flexible scheduling could achieve shorter durations, more leveled histograms, and less total cost. Besides leveling and allocation, Flexible Scheduling could perform an overall schedule cost optimization taking into consideration leveling, allocation and efficiency losses resulting from different scenarios. The results of cost optimization are adequate as the minimum cost is achieved by utilizing scenarios, different from the normal one, meaning that efficiency trade-off is performed and an optimum point is attained.

5.2 Conclusions

Flexible Scheduling enhances the results from CPM and the current techniques used to enhance its schedules. The model is successfully utilized to solve different objectives such as resource leveling, resource allocation, cost optimization, and cost optimization with resource constraints. For each objective, Flexible Scheduling found better solution when offering three-sided tradeoff between cost, time and efficiency. In the case for resource leveling, results extracted by Flexible Scheduling outperformed classical solutions in terms of minimizing variations; however, an additional marginal cost resulted from the selected scenarios. Hence, a new cost of leveling was introduced such that project managers can decide to trade for better leveled resources. In addition, with the rest of objectives, solutions provided by Flexible Scheduling outperformed current techniques in terms of time and cost despite the increase in labor cost. The results are detailed and handy such that it tells for each activity how many workers to be assigned and for how many working hours per day.

5.3 Limitations of Current Study and Recommendations for Future Works

In this research, productivity losses associated with crowding and overtime were calculated using Hinze [**4**] equations. The adequacy of these empirical equations might not be convenient for certain environments or companies. Hence, it is recommended to implement data based on each case's attributes either by regression or expert judgment to generate the scenarios. This addition can be implemented without affecting the model as the scenarios extraction are in isolation of the modeling – Pre-modeling. In addition, other adjustments can be implemented in the model such as learning curves for repetitive projects, increasing number of working days per week, and increasing number of work starting points.

Flexible Scheduling model has a complex nature in terms of the number of variables and constraints, type of functions, and interrelated attributes. Therefore, calculation time is long for projects that have complex relations and high number of activities. In addition, the more man-hours required for the activity, the more scenarios can be generated and consequently increase the problem complexity. The model running is time consuming (in some cases, taking up to 29 hours for running an objective) and reflected software crashing when the problem contains large number of activities. Hence, *What'sBest* ability to solve large-scale problems is limited. Flexible scheduling can be modeled using other powerful heuristics like Genetic Algorithms or Particle Swarm to overcome this limitation.

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VITA

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After graduating, Mr. Saleh has worked for two years as a project engineer in an oil and gas construction firm. He then moved to the general construction sector. In 2009, Mr. Saleh began a master's program in Engineering Systems Management with a concentration in Construction Management at the American University of Sharjah. He was awarded the Master of Science degree in Engineering Systems Management in 2012.

Mr. Saleh is a member of the Project Management Institute, the American Society of Civil Engineers and the Jordanian Engineers Association.