CSCanada
Management Science and Engineering
Vol. 6, No. 4, 2012, pp. 120-125
DOI:10.3968/j.mse.1913035X20120604.889

ISSN 1913-0341 [Print]
ISSN 1913-035X [Online]
www.cscanada.net
www.cscanada.org

Implementations of Spreadsheet Modeling for Generalized Critical Path Method

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Received 20 October 2012; accepted 10 December 2012

Abstract

Using Excel or any form of spreadsheet for project scheduling is a convenient approach. The approach is dynamic compared to traditionally manual computations. It is also less complicated and mechanistic and rather straightforward compared to advanced programming languages. This paper intends to investigate numerous implementations of spreadsheet modeling ever worked and resulted for generalized critical path method. The approaches produced have significantly contributed to the advancements of teaching and learning and computerized applications in management science and industrial engineering. The approaches are comprehensively discussed, the advantages of respective approaches are thoroughly reviewed, their limitations are carefully addressed, and significant findings from the approaches presented are evidently derived.

Key words: Critical path method; Spreadsheet modeling; Project scheduling; Operations research; Management science; Quantitative method; Industrial engineering

Khairul Annuar Abdullah, Wan Azlan Wan Hassan, Mohd. Fahmi Mohamad Amran, Suziyanti Marjudi, Norhawani Ahmad Teridi, Zuriati Yusof (2012). Implementations of Spreadsheet Modeling for Generalized Critical Path Method. *Management Science and Engineering*, *6*(4), 120-125. Available from: http://www.cscanada.net/index.php/mse/article/view/j.mse.1913035X20120604.889
DOI: http://dx.doi.org/10.3968/j.mse.1913035X20120604.889

INTRODUCTION

A project is defined as a collection of interrelated activities with each activity consuming time and resources (Taha, 2007). A project is a well-defined set of jobs, tasks, or activities, which must be completed in a specified time and sequence order (ICAN, 2009). These activities are divided into manageable work packages known as work breakdown structure. They are connected by logical sequences and some activities may not begin until some another activities finish. These circumstances are called precedence/predecessors relationships. Each activity has an estimate of duration. This estimate of duration may be expressed as a single value or in the form of optimistic, most likely, and pessimistic values (Baker, 2005). Project management reflects a commitment of resources and people to a typically important activity for a relatively short time frame (Taylor III, 1996). Better project management can be developed by increasing the number of project management (Shtub, 1997).

Bodily (1986) has suggested using spreadsheets for modeling operations research and management science problems. Using spreadsheets as a key medium of instruction clearly is one new wave in teaching of operations research due to its comfortable and enjoyable learning environment (Hillier & Lieberman, 2001). Spreadsheet is used to simplify modeling and to simplify its use by practitioners (Hegazy & Ersahin, 2001). Spreadsheet is the best way to do most modeling as it is capable to build more detailed and more complex model than traditional mathematics (Powell & Baker, 2009). Spreadsheets like Excel and alike have gained popularity among project planners, managers, and schedulers in building models for decision-making. The planners, managers, and schedulers are accustomed and feel convenient, as the spreadsheets have natural interfaces

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suitable for model building: easy to input, capability of carrying out what-if analysis, presentable output, and automated report generation (Seal, 2001). The spreadsheet Excel is an ideal medium for constructing network models and performing critical path analysis (Baker, 2005).

Figure 1 depicts the layout of spreadsheet modeling for generalized critical path method (CPM) formulated by Winston and Albright (1997).

ROOM CONSTRUCTION PROJECT

Data on Activity Network

Activity	Index	Predecessor	Duration
Prepare foundation	A	None	4
Put up frame	B	A	4
Order custom windows	C	None	11
Erect outside walls	D	B	3
Do electrical wiring	E	D	4
Do plumbing	F	D	3
Put in duct work	G	D	4
Hang dry wall	H	E,F,G	3
Install windows	I	B,C	1
Paint and clean up	J	H	2

Explanation:
C5-D14: Information on precedence relationships of activities and durations
B18-B25: Information on the latest times of nodes
D18-F28: Information on AOA project network
G18-G28: Information on the latest finish times of events
I18-I28: Information on the earliest start times of events + durations of activities

Node Event Time, Δ

Node	Time
1	0
2	4
3	8
4	11
5	15
6	19
7	18
8	20

Arc (Activity), Corresponding Node, and Time Constraint

Activity	Start Node	End Node	End Time, Δ_j	Constraint	Start Time + Duration, [illegible] + D = [illegible]
A	1	2	4	>=	4
B	2	3	8	>=	8
C	1	6	19	>=	11
D	3	4	11	>=	11
E	4	5	15	>=	15
F	4	5	15	>=	14
G	4	5	15	>=	15
H	5	7	18	>=	18
I	6	8	20	>=	20
J	7	8	20	>=	20
Dummy	3	6	19	>=	11

Project Time 20

Figure 1
Spreadsheet Modeling for Generalized CPM

"Modeling in spreadsheets is more an art than a science as there is no systematic procedure that invariably will lead to a single correct spreadsheet model" (Hillier & Hillier, 2004). Thus, this study is dedicated on investigating diverse approaches ever worked for generalized CPM modeling using spreadsheets that have given huge impacts to the teaching and learning and computerized applications in management science and industrial engineering.

LITERATURE REVIEW

The critical path method (CPM) is vastly applied from government agencies to non-profits and from engineering companies to service industries. CPM was mostly developed for construction, production, and maintenance projects (Winston & Albright, 1997; Hillier & Hillier, 2004; ICAN, 2009). CPM is a network-centric method derived to facilitate planning, scheduling, and control of a project (Taha, 2007). CPM is a standard network-based technique commonly used for scheduling (Shtub, 1997). Its objective function is the minimization of project duration (Fung, Huang, & Tam, 2011). The method was resulted during the development of a computerized system to improve the planning, scheduling, and reporting of the company's engineering programs (Taylor III, 1996). Since time schedule or Gantt chart is not able to determine relationships and dependencies of activities, CPM is necessary to plan and execute a project systematically and effectively. With CPM, project planners, managers, and schedulers are able to make decisions regarding scheduling and resource assignments to shorten the time required for critical activities that will impact projects' deadlines (Marchewka, 2010). The advantage of CPM over the Gantt chart is in the use of a network, instead of a graph, to show the precedence relationships between activities. A network also often can be easily explained compared to a set of mathematical equations. Another advantage of CPM is the method may establish a trade-off for optimum balancing between scheduled time and cost of the project.

The procedure of project scheduling using CPM is indicated in Figure 2 (Taha, 2007).

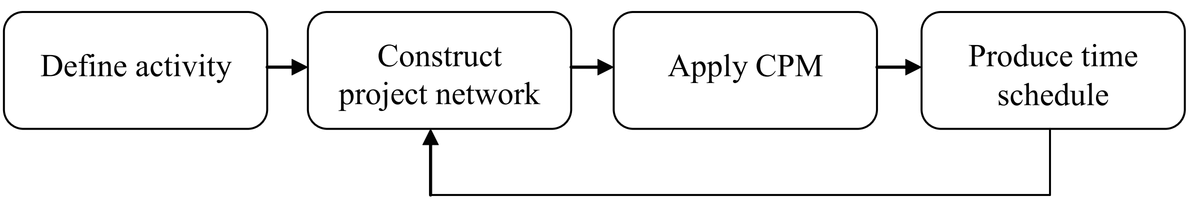

Figure 2
Phases of Project Scheduling with CPM

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In "define activity" phase, activities of a project, their precedence relationships, and their estimates of duration are determined.

In "construct project network" phase, the activities are represented through a project network called network diagram. The project network provides a graphical representation of the precedence relations among all the activities in a project (Winston & Albright, 1997; Carter & Price, 2001). The project network built is able to support the development of the project schedule by identifying dependencies and the sequencing of the activities defined in the work breakdown structure (Marchewka, 2010). There are two conventions commonly used notably, activity-on-node (AON) and activity-on-arc (AOA) as respectively indicated on Figure 3 and Figure 4.

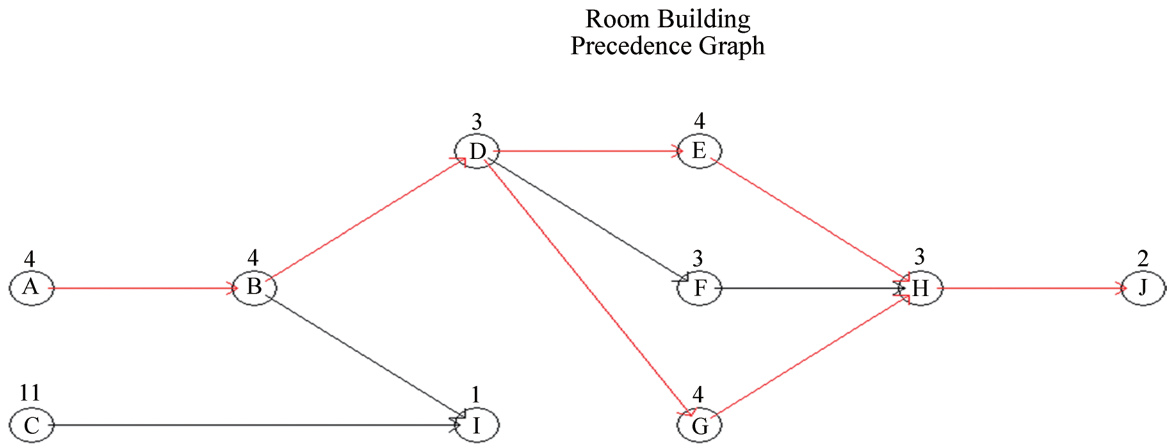

Figure 3
Project Network of AON in QM for Windows

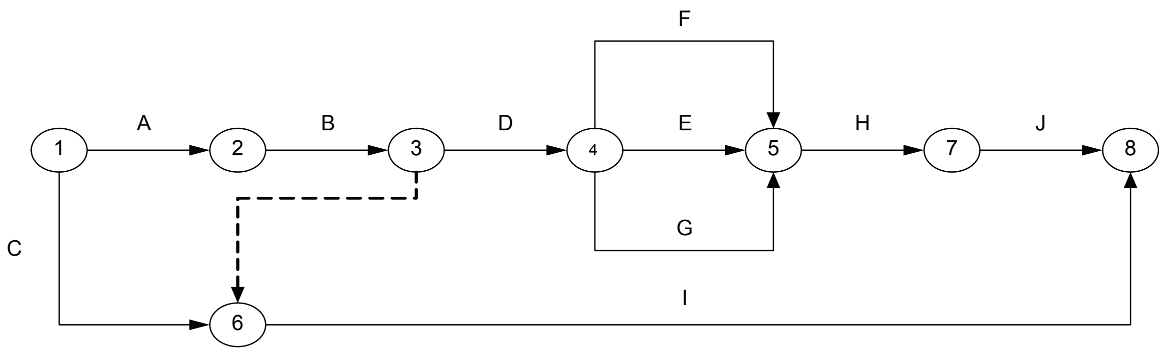

Figure 4
Project Network of AOA in Microsoft Visio

AON project network is considerably easier to construct, to understand for many inexperienced planners, managers, and schedulers, and to revise when there are changes in the project (Hillier & Hillier, 2004). Those important advantages the AON project network a practice in industries. One of the advantages of AON over AOA is that dummy activities are not required in an AON network. However, there is no computational proof to support that one is better than the other (ICAN, 2009) and is usually a matter of individual preference (Taylor III, 1996).

In "apply CPM" phase, passes: forward pass and backward pass, and floats: total float and free float, are computed. The reason for the former pass is to determine earliest times and find the project total duration. The purpose of the latter pass is to determine latest times, critical path(s) and activities, and non-critical activities. The critical path is the longest path in the project network and is also the shortest time in which the project can be completed (Marchewka, 2010). An activity is critical if there is no leeway in determining its start and finish times (Taha, 2007). The term float refers to the period of time by which a particular activity can be delayed without the time schedule of network affected (ICAN, 2009). They are slack times permitted for non-critical activities. Project planners, managers, and schedulers perceive floats as important, as resources of activities with floats might be temporarily withdrawn and used for other activities. By scheduling non-critical activities, the management may consider possible improvements in the project schedule or evaluate the effects of delays along the critical path (Carter & Price, 2001). The total float of an activity is the maximum amount of time the activity can be delayed from

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its earliest start time (EST) without delaying the critical path. The free float refers to the maximum allowable delay from the EST of an activity without delaying the EST of any of its immediate successor activities. The computations of CPM are illustrated in Table 1 (Taha, 2007; ICAN, 2009).

Table 1
Computation of CPM

No	Computation	Formula
1	Expected Time	$t = (a + 4m + b) / 6$
2	Variance of Activity Time	$\sigma^2 = [(b - a) / 6]^2$
3	Probability of Completion Time	$P\,[Z = (T - \Sigma t_{critical}) / \sigma]$
4	Forward Pass	$\square_j = max\ \{\square_p + D_{pj}, \square_q + D_{qj}, \square_r + D_{rj}, \ldots, \square_v + D_{vj}\}$
5	Backward Pass	$\Delta_j = min\ \{\Delta_p - D_{jp}, \Delta_q - D_{jq}, \Delta_r - D_{jr}, \ldots, \Delta_v - D_{jv}\}$
6	Total Float	$TF_{ij} = \Delta_j - \square_i - D_{ij}$ for AOA $LST - EST$ or $LFT - EFT$ for AON
7	Free Float	$FF_{ij} = \square_j - \square_i - D_{ij}$ for AOA $EST_{successor} - EFT_{predecessor}$ for AON
8	Critical Activity	$\Delta_i = \square_i$, $\Delta_j = \square_j$, and $\Delta_j - \Delta_i = \square_j - \square_i = D_{ij}$ for AOA $LST - EST = LFT - EFT = 0$ for AON

Formulae 1 until 3 are applied when the durations of activities are probabilistic (Hillier & Lieberman, 2001; Taha, 2007). Three time estimates of performance are employed: optimistic time, most likely time, and pessimistic time. As for Formulae 6, 7 and 8, they differ due to the project network conventions used.

In "produce time schedule" phase, a project Gantt chart based on the sequencing and time estimates of the activities is generated. The backward arrow depicts things in reality, may not proceed as planned, as the activities may expedite or delay. Thus, the time schedule must be revised.

RESULTS AND DISCUSSION

Many excellent textbooks in Operations Research (OR), Management Science (MS), Quantitative Method (QM), and Decision Science (DS) as Taylor III (1996) and Winston and Albright (1997) formulate CPM using linear programming (LP) with Excel Solver. Choosing the activity-on-arc as the standard convention for the project networks, the approaches follow exactly the LP procedure: define the decision variables, objective function, and constraints. The approach considers the earliest event time at each node x_i or x_j, as this is the earliest time that the completion of all predecessor activities leads into it or the start of all successor activities leaves it. The objective function is expressed as *minimize* $Z = \sum_i x_i$. This objective function serves to ensure the earliest event time at each node. While the time of activity (i, j) is referred as t_{ij}, the difference between the earliest event time at node j and the earliest event time at node i must be at least equal to the activity time t_{ij}, notably $x_j - x_i \geq t_{ij}$. Winston and Albright (1997) particularly apply the VLOOKUP function to respectively calculate LFT and EFT.

Seal (2001) proposes a means of modeling the critical path method (CPM) that caters the extendibility of model up to 200 activities. This approach allows activities to be added or deleted and precedence relationships to be altered. The approach applies an activity-on-node convention to construct the project network. The concept of matrix whereas is used to represent the precedence relationship of activities and to calculate the earliest start time (EST), earliest finish time (EFT), latest start time (LST), and latest finish time (LFT). The total float computation *LST-EST* is adopted to determine whether an activity is critical.

Ragsdale (2003) adopts array formulae and circular references for CPM modeling, particularly to calculate EST and LFT of each activity. This approach improves Seal's by enabling activities to be added or deleted and precedence relationships to be altered regardless of the size of project by only copying formulas without changes.

Davis (2005) employs milestone nodes when there are multiple beginning and/or ending nodes in a project network. Modifying Seal's precedence matrix, the relationships of activities are represented via so-called successors and predecessors matrices. From the matrices, two pointer lists are derived: successors pointer list and predecessors pointer list. The lists contain the number of time an activity becomes a successor/predecessor and the index number(s) of succeeding/preceding activity(ies). The OFFSET function and array formula are used to compute the activity's EST and LFT. The Visual Basic for Applications (VBA) macros whereas are programmed as comparisons to perform CPM's forward pass and backward pass.

Baker (2005) utilizes spreadsheet, VBA, and Applications Programming Interface to develop a computer-aided learning (CAL) and assessment for CPM with twofold objectives in mind: as a self-learning tool for students and as a self-assessment tool for academicians. In the CAL module, students are able to self-learn on how to compute by hand/reason the CPM analysis through the visual of project network, practice the spreadsheet modeling to analyze CPM, and construct the project network. The Tools Auditing (Formula Auditing in Excel 2010) feature, not least Trace Precedents and Trace Dependents has been used to automatically appear the arrows of project network.

The different implementations of spreadsheet modeling for generalized CPM are summarized and compared in Table 2.

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Table 2
Implementation of Spreadsheet Modeling for Generalized CPM

No	Author	Advantage	Limitation
1	Taylor III (1996), Winston and Albright (1997), and many textbooks in OR, MS, QM, and DS	Less complicated in modeling due to the Solver feature.	1. Inflexible and problem-specific. 2. Not straightforward as requiring conversions to LP.
2	Seal (2001)	Scalable, flexible, and extendible approach.	1. The mechanic of matrix is rather complicated. 2. The number of activities is limited up to 200.
3	Ragsdale (2003)	1. Capable to accommodate any number of activities. 2. The precedence relationship is alterable without manually amending the formula. 3. Amenable to simulation for variable activity durations.	1. Four nested functions are rathercomplicated. 2. Careful in activities labeling with *FIND* (x, y) function.
4	Davis (2005)	1. Milestone nodes avoid ambiguities on where a project begins and/or ends. 2. The array is compact as the range is only the pointer list instead of the number of activities in a project. 3. VBA macro is dynamic compared to built-in functions.	1. Several nested functions are rather complicated. 2. Familiarity in VB programming is necessary.
5	Baker (2005)	1. CAL approach is attractive and fun than the traditional learning. 2. Self-learning feature that improves flexibility in time and learning pace. 3. Self-assessment feature that improves efficiency and effectiveness in marking and minimal supervision. 4. The project network is madevisualized for interactivity. 5. Learners are able to experience themselves to perform spreadsheet modeling for CPM. 6. The problems (tables of predecessors) are randomly (using random numbers) generated and the activities are permuted. 7. The project network and CPM analysis are compiled and made printable.	1. The number of nodes (activities) for a project network is fixed to 9 excluding the start and end nodes. 2. Familiarity in VB programming such as subroutines is necessary. 3. Security is potentially compromised as the spreadsheet might be breached to modify the code and unhide sheets.

Based on the details of modeling approaches discussed and the table of comparisons resulted, it is vital to highlight the following findings:

Functions in spreadsheet as VLOOKUP/HLOOKUP, FIND, OFFSET with MAX/MIN, its add-in: Solver, its feature: Tools Auditing (Formula Auditing), and the Visual Basic for Applications macro are found useful for modeling generalized CPM.

Modeling CPM using spreadsheet is found flexible to accommodate any number of activities and to alter the activities' precedence relationships without the needs to manually amend formulae and layout/interface.

Spreadsheet modeling for CPM is found very applicable to extend to computer-aided learning platform for students and computer-aided assessment tool for academicians.

It is found that the Visual Basic for Applications macros have made possible to randomly generate the table of predecessors, permute the activities, interact with and compile the project network, and perform CPM analysis.

Despite improvements and enhancements undertaken, security is found remains as the main issue of any spreadsheet modeling applications until to-date.

CONCLUSION

This paper has scrutinized various approaches for modeling generalized critical path method (CPM) with spreadsheet. The diversities of these modeling styles have greatly improved the aspects of teaching and learning and computerized applications in management science and industrial engineering. The advantages of the approaches have been reviewed, the limitations of them have been addressed, and the important findings have been emphasized.

Researches on spreadsheet modeling including for CPM have been elevated to greater heights. Presently towards the future, the implementations of spreadsheet

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modeling are integrated with optimization/machine-learning techniques: genetic algorithm, fuzzy logic, neural network, simulated annealing, ant colony, particle swarm et cetera for many uses and benefits.

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