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CONSTRUCTION PROCEDURE OF A STRAW BALE WALLED BUILDING – A REVIEW

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ABSTRACT: This study highlights the use of plastered straw bale as a load bearing element, its method of construction and specification required to obtain maximum benefits from the use of this material. Critical Path Analysis (CPA) was used in formulating, scheduling and managing the various milestones or activities in the construction of a plastered straw bale walled building. CPA arising from this work provides an empirically constructed schedule of planning activities for straw bale wall and other auxiliary building elements (foundations, roof, lintel and brick columns) to meet some self-imposed or institutionally required calendar of events. The critical path analysis was developed using Microsoft Visual Basic 6 Software to determine the critical path in the construction schedule. The construction basic data are input into the activity interface which comprises the activity name, description, predecessor activity, start node and end node. The economic analysis of the construction work has shown that the total actual cost of the residential building is 0.77 of the same building built with sandcrete wall with scheduled times of 29.64 and 28.64 weeks respectively.

KEYWORDS: Automation, construction, straw bale, plaster, critical path analysis

❖ INTRODUCTION

This study demonstrates the utility of Microsoft Visual Basic and Microsoft Excel in generating construction project plans using the critical path method (CPM) to establish and maintain a reasonable and acceptable construction schedule for a bungalow residential building, constructed with straw bale walls and other auxiliary structural members (brick columns, slab and lintel beams). General principle from experienced human planner and physical laws has been utilized.

The study also develops a computer program that gives a step by step procedure in the construction process using Microsoft Visual Basic and Microsoft Excel Programming. Also a successful management of any construction work depends largely on how early such a project is completed. Therefore, the determination of the critical path in the construction process will help the management to keep abreast with the task ahead and thereby prevent any delay in all the activities along the path.

❖ STRAW BALE

The use of straw is one of the oldest construction methods in our present day. Stone was probably the first material to be used in construction and though it is still in use today, other materials like bricks, timber, concrete and steel have been developed and used alongside (Blum 2002, Catherine, 2001, Bou-Ali 1993). Some factors that affect choice of materials for wall construction are:

- i) The particular functions of the wall which will limit the choice of material by the designer.
- ii) The structural form of the building determines whether a wall is to be load bearing or non-load bearing, hence the nature of the loading and the load carrying capacity of the material will restrict the choice of certain materials.
- iii) Some special selection of materials may be available from only one supplier which may lead to long waiting period before an order can be fulfilled. Hence, the natural economic climate may mean that some of the more common materials, which are under normal circumstance readily available, may be used.
- iv) The speed of construction of the wall may lead to use of materials that would meet the need of that time.
- v) The cost of material may lead to choice of less costly but suitable material for use.
- vi) Also, the cost of labor for the construction of the wall and any subsequent finishing costs.

FUNCTIONS OF WALLS

The importance of these functions will depend upon the type of structure which is to be erected, the situation of the building in terms of both macro and micro environment and the use for which the building is intended.

- Strength and stability: - The wall should be strong enough to carry imposed load without excessive deformation. The strength of a wall depends on the strength of the material of the wall and its (wall) thickness (Ruppert and Grandseat 1999, Adedeji 2002, 2007).
- Weather exclusion: - It is extremely important to keep weather out of a building if the internal environment is to remain constant.
- Thermal insulation: - Heat flow from higher to a lower temperature (conduction). Heat loss from external walls can be reduced by means of insulation; there is a wide difference in the range of thermal conductivity of various engineering materials (Otiki 2004, Catherine 2001).
- Durability: - The material from which external walls are constructed must have sufficient resistance to the damaging effects of the climate in the form of erosion, atmosphere pollution, rain and chemical and solar radiation (Platts 1977, Ruest 2000).
- Sound Insulation: - Noise has been defined as unwanted extremely loud sound which can be detrimental to health, irritating and can cause loss of concentration. Thus, sound transmits less in medium which are air tight. Walls do not permit the direct passage of successive air pressure through their material.
- Services like electric lighting and power points, gas outlets, water pipes, telephone and television outlets etc. must pass through, or be fixed to the wall. Thus, the material of the wall must therefore be able to accommodate them without loss of strength.
- Attachment: - Cupboards, shelves and other storage units that are hanging and fixed to the wall must be catered for.

STRAW BALE WALL TYPES

There are two primary forms of straw bale construction, load bearing and non-load bearing (Chris and Peter, 2000). In non-load bearing straw bale construction, the bales serve primarily as in-fill insulation, although their function as a mesh to directly hold plaster gives another significant benefit. In load bearing structures, the weight of the roof and lateral shear pressures are actually carried by the bales and the plaster which encase them. Two string bales are used which is considered best suited for non-load-bearing application while three string bales are thus more appropriate for load bearing application. Straw, waste stalks from wheat, rye, etc harvest are first collected together and compacted into bales. To build a load bearing wall, the bales are tied with three strings using polypropylene twine or bailing wire (Bainbridge, 2000). The foundation is prepared with 12mm threaded rods to make the first layer and the next layer is pushed on top. More rods are pushed in and each successive layer is added. The windows and doors were framed and the openings are cut into the bales. Bales are stacked in a running bond i.e. the second layer or course of bale are staggered atop the first so that the middle of each bale in the next higher layer is located over the beam between two bales on the lower layer. This (stacking) using a running bond produces a wall that is stronger and more stable. A wooden box beam can be used as the top plate to support the roof.

The threaded rod protruding through the box beam fastens the entire wall together. The conduit work, wiring and plumbing are placed in the grooves between the bales. In non-load bearing wall, the straw bale is used as wall in-fill between the structural members (columns, beams etc.); it supports only its self weight. The straw bale overhangs the bearing surface by not more than 100mm and maximum height of 300mm and length of 6m for unbuttressed in-fill wall panel (New Mexico straw bale construction guidelines, 2001). After the Straw bale is laid to beam level and conducting work is completed then plastering work commences using cement plaster of ratio 1:6 or 1:8.

❖ METHODOLOGY

CRITICAL PATH ANALYSIS

The critical path method is basically simple but very powerful technique for analyzing, planning, and scheduling large complex projects (Archibad and Richard, 2004). It provides a means of determining which activities, of many of which comprises the total project, are “critical” in their effect on overall completion time and how best to schedule all activities involved in the project in order to meet a specific target date at minimum cost. It accomplishes this by a clearly designed series of steps which may be described in logical terms such that they lend themselves to analysis by the electronic computer, thereby making available the power of this device to handle large quantities of data with high speed and accuracy.

The basic steps in Critical Path Method (CPM) are followed in these findings:

- ❖ The work is distributed into individual jobs or activities.
- ❖ The precedence relationships among jobs are determined.
- ❖ The arrow diagram or project network is drawn. They represent precedence relationship.
- ❖ Job durations are estimated.
- ❖ CPM are used to schedule activities over time to minimize project duration
- ❖ During operation, if any job is delayed, use CPM to revise schedule for remaining jobs.

CPM PROJECT PLANNING STEPS FOR STRAW BALE WALL

Specifying the individual activities: From the work breakdown structure, a listing is made of all the activities in the projects. This listing is used as the basis for adding sequence and duration information in later steps.

- ❖ Determining the sequence of the activities: Some activities are depended on the completion of others. The listing of the immediate predecessors of each activity is useful for constructing the CPM network diagram (Harold, 2003).
- ❖ Drawing the Critical Path Network diagram: Using the activities and their sequence, the CPM diagram is drawn.
- ❖ Estimating activity completion time: The time required to complete each activity is estimated using past experience in the construction industry. CPM is a deterministic model that does not take into account variation in the completion time, so only one number is used for an activity’s time estimate.
- ❖ Identifying the critical path: The critical path is the longest-duration through the network. The significance of the critical path is that the activities that lie on it cannot be delayed without delaying the project. The critical path is identified by determining the following four parameters for each activity:
 - ES-earliest start time: the earliest start time at which the activity can start given that its precedent activities must be completed first.
 - EF- earliest finish time: equal to the earliest start time for the activity plus the time required to complete the activity as shown in equation (1).
 - ❖ Earliest time for an event E_j = the time event j will occur if the preceding activities are started as early as possible.
 - ❖ Forward pass: Computing E_j for each event j beginning at the first node and moving forward.
 - ❖ Early time rule: E_j is the maximum of the sums $E_i + t_{ij}$ involving each immediately preceding event i and intervening activity ij .

$$E_j = E_i + t_{ij} \tag{1}$$

- LF- latest finish time: the latest time at which the activity can be completed without delaying the project.
- LS-latest start time: equal to the latest finish time minus the time required to complete the activity as shown in equation (2).
 - ❖ Latest time for an event: L_i = the latest time that event i can occurs without delaying completion of the project beyond its earliest time.
 - ❖ Backward pass: Computing L_i for each event i beginning at the last node and moving backward.
 - ❖ Latest time rule: L_i is the minimum of the differences $L_i - t_{ij}$ involving each immediately following even j and intervening activity ij .

$$L_i = L_j - t_{ij} \tag{2}$$

- Slack time (time that an activity can be delayed past its earliest start (ES) or earliest finish without delaying the project.): ES is the length of a longest path from START node to tail of activity arc,

$$\text{Slack time for activity } ij = LS - ES = (L_j - t_{ij}) - E_i \tag{3}$$

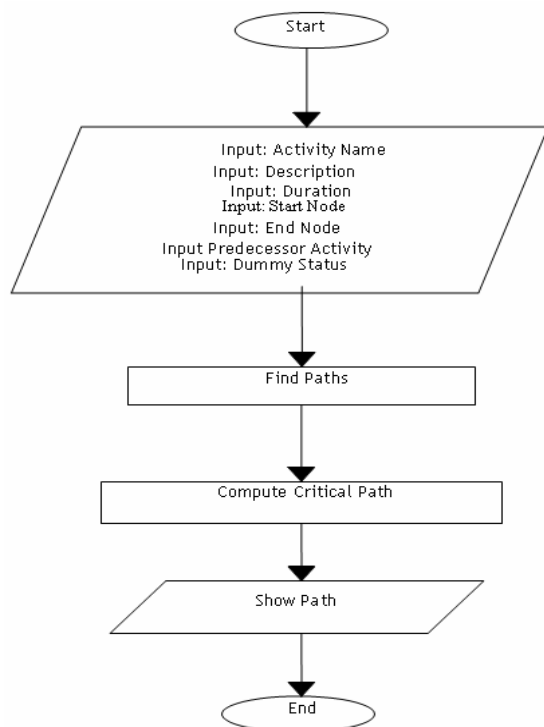


Figure 1. Program Flow Chart

The critical path is the path through the project network in which none of the activities have slack, that is, the path for which $ES = LS$ (LS = latest time a given activity can start without delaying the project) and $EF = LF$ for all activities in the path. A delay in the critical path delays the project. Similarly, to accelerate the project it is necessary to reduce the total time required for the activities in the critical path.

FLOW CHART

The Visual Basic Program written takes as input the details of each activity (Activity Name, Duration, Description, Start Node, End Node, Predecessor Activity, and Dummy Status). After all activities have been added, the paths are found by clicking on the “Find Path” button below the activity list.

The program then proceeds to find all possible paths and compute the critical path. The program flow chart is shown in Figure 1, while the activities flow chart is shown in Figure 2. The Visual basic program codes are attached in the appendix.

ANALYTICAL EXAMPLE AND RESULTS

The building considered in this study is a bungalow residential building of straw-bale walls and other auxiliary structural members (brick columns, slabs and lintel beam). It is made up of three bedrooms flat. The plan dimensions are 9,900mm by 12,600mm. The building plan is shown in Figure 3.

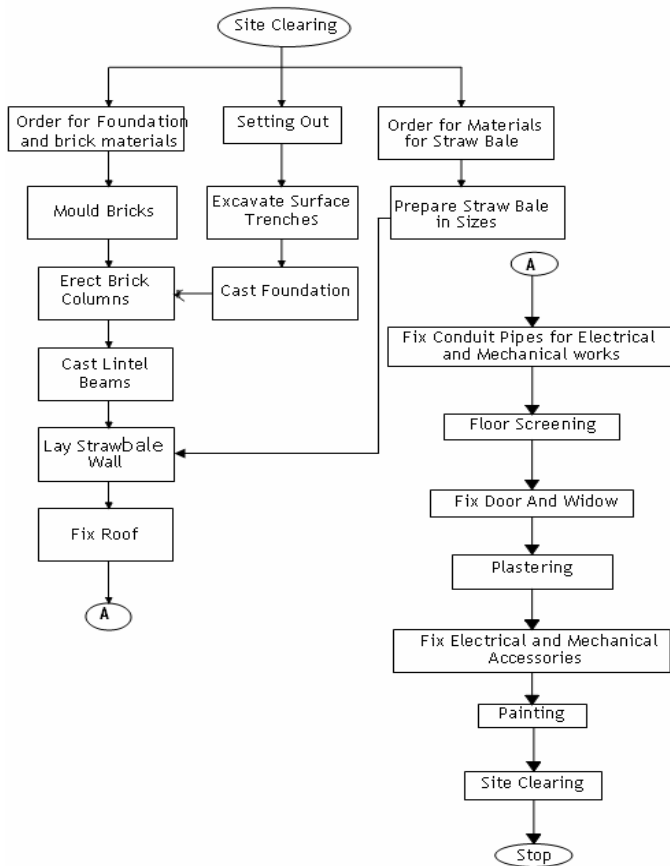


Figure 2. Activities Flow Chart control

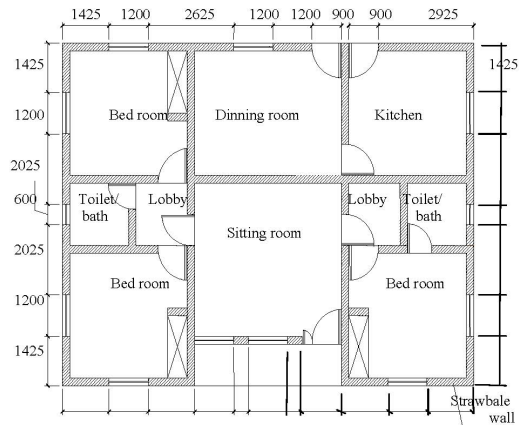


Figure 3. Plan of the building

PROGRAM OF WORK SCHEDULE

Using Fig. 3, a program of work schedule for the construction of the building using straw bale walled structure is derived. A program of work schedule was developed using experience and past knowledge to breakdown the construction activities in sequential order taking into cognizance the principle of ordering as explained in chapter three. In the calculation of the duration for each activity, the quantity of work involved, the number of labor, equipment available and the time required for some activity to achieve the necessary compressive strength resulted in Table 1.

Table 1. Program of work schedule and duration of activities

Activity	Description	Duration (weeks)
A	Site Clearing	1
B	Order for Foundation and Bricks materials	1
C	Setting out of the building plan	0.14
D	Excavation of surface trenches for the strip foundation	2
E	Order Materials for Straw bale	7
F	Cast foundation	4
G	Mould Bricks	3
H	Erect Brick Columns	2
I	Cast Lintel Beams	4
J	Prepare straw bale in sizes	3.5
K	Lay Straw bale wall	3.5
L	Fix Roof	2
M	Fix conduit pipes for electrical and mechanical works	2
N	Fix ceiling board	1
O	Floor Screeding	1
P	Fix Doors and Windows	1
Q	Plastering of the wall	3
R	Fix Electrical and Mechanical Accessories	1
S	Painting	2
T	Site Cleaning	1

APPLICATION OF CRITICAL PATH ANALYSIS

The utilization of the critical path analysis basic principles, procedures, and definitions gave rise to the terminology and processes described below.

Step One: Listing of the major activities

Listing of the major activities was done through a thorough analysis of the steps involved in initiating, implementing and bringing to culmination a successful planning endeavour. The activities were broken down as shown in Table 2.

Step Two: Sequencing the major activities

The next step is the sequencing of each activity based on when it must or is most likely to occur. The activities that precede other activities were identified. This step was carried out by the reshuffling of the activities and this cumulated in the final sequence shown in Table 3.

Step Three: Constructing an Activity flow diagram.

The third step was the construction of a schematic or flow diagram detailing the sequence of activities for the overall planning of the project. The under listed steps were used in constructing the flow diagram shown in Figure 4 below.

- Event - the start or completion point of an activity. Events do not consume time or resources, but are used as notations in constructing a critical path analysis network.
- Activity - the performance of an activity. Activities do consume time and/or resources.
- Network - the flow diagram is constructed by connecting events; this details the sequence of activities for the project as shown in Figure 4.

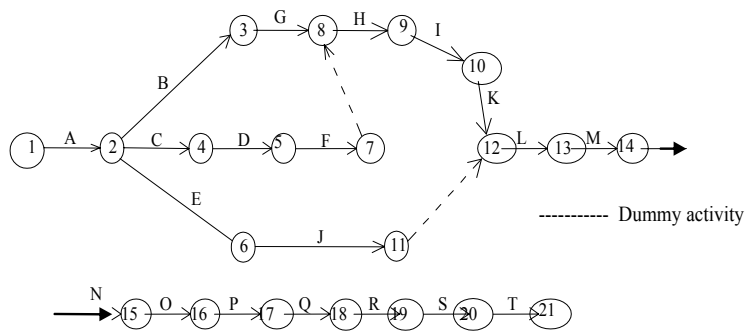


Figure 4. CPA network diagram

Table 2. Lists of major activities

Activity	Description
A	Site clearing
B	Prepare and stack straw bale in sizes
C	Setting out
D	Excavate surface trenches for foundation
E	Cast foundation
F	Erect brick columns
G	Order for foundation and bricks materials
H	Order material for straw bale
I	Cast lintel beams
J	Fix ceiling board
K	Fix conduit pipes for electricity & mechanical work
L	Painting
M	Floor Screeding
N	Mould bricks
O	Lay straw bale wall
P	Fix doors and windows
Q	Plastering
R	Fix roof
S	Fix electrical and mechanical accessories
T	Site cleaning

Table 3. Sequencing of construction activities

Activity	Description
A	Site clearing
B	Order for foundation and brick materials
C	Setting out
D	Excavate surface trenches for foundation
E	Order material for straw bale
F	Cast foundation
G	Mould bricks
H	Erect brick columns
I	Cast lintel beams
J	Prepare straw bale in size
K	Lay straw bale wall
L	Fix roof
M	Fix conduit pipes for electrical & mechanical work
N	Fix ceiling board
O	Floor Screeding
P	Fix doors and windows
Q	Plastering
R	Fix electrical and mechanical accessories
S	Painting
T	Site cleaning

Step Four: Estimating the time for an activity.

The estimation of the required time for an activity is based on judgment and experience in the construction industry, the number of skilled and unskilled labor that are available for the construction work, resources in terms of equipment to be used and availability of fund to recruit staff and hire the required equipment needed for the construction (Amarijit and Upadhyay, 2007). The computation of the duration and rate for each activity takes into cognizance the following under listed items:

- (i) Labour: These are the qualified tradesmen and labor performing all kinds of labor works on the site,
- (ii) Materials: These are the materials required for the execution of the project. The costs of delivery to site, loading and offloading of the materials are also included in the unit cost.
- (iii) Equipment: These are the equipment necessary for the execution of the project. These include head pans, shovels and diggers and
- (iv) Labor and material proportion

Table 4. Labor output constant

S/no	Description	Quantity per day	Labor
1	Excavation and earthwork	2.27m ³	per labor
2	Concrete work	3 27m ³	per mason
3	Brick/Block work	10 27m ²	per mason
4	Plaster work	1027m ²	per mason
5	Painting	1827m ²	per painter

Source: Amarjit and Upadhyay, 2007

Practically very few items in

a bill of quantities are labor only. All other items which form the majority of the works are made up of labor and material. The Table 4 shows the labor output constant for different work.

The standard output of each labor involved in a particular activity determines the total number of such labor needed to complete the activity in focus. Using the excavation of the foundation trenches as an example: - The total quantity to be excavated is 27.27m³ i.e. 93.6m x 0.45m x 0.6m. From the table, the standard output of a labor involved in excavation is 2.27m³ per day. Allowing 8% addition to the quantity, to allow for unforeseen situation, gives a total excavated quantity as 25.27 x 1.08 = 27.29m³. Therefore, two labors working for six days at ₦1,500 per day per labor and one artisan serving as supervisor for two days at ₦2,000 per day per person give the total amount required to complete the excavation work as ₦22,000.00.

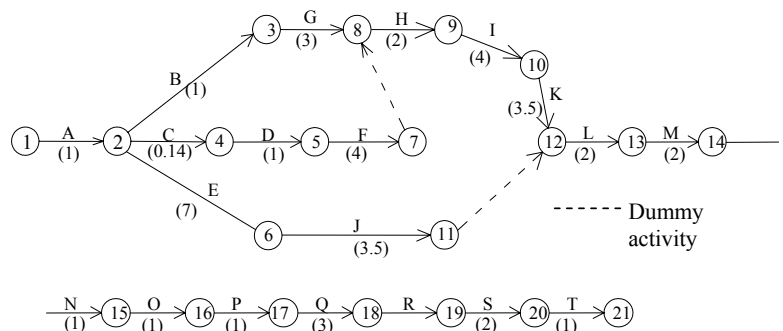


Figure 5. CPA network displaying estimated times (wks) to complete each activity

Figure 5 displays the previously constructed network with time estimates included. They are displayed as numbers below an activity arrow. The network utilizes an 8-hour working day and a seven-day week, assuming that weekend and overtime costs will be computed when the need arises. In the international scene US\$1 ~ ₦ 152 (Naira in August, 2010)

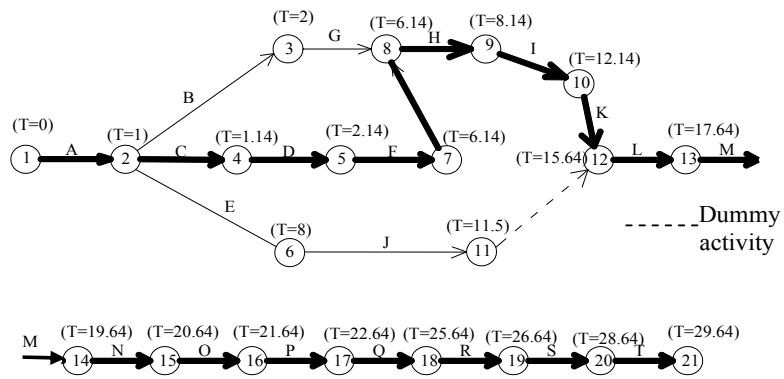


Figure 6. CPA Network for the total time in weeks at each event

Step Five: Computing the expected times to complete all activities

Following the estimation of the time required for each activity, the earliest possible time that each event could be reached was calculated as shown in Figure 5 by the letter “T”. This total is derived by summing the estimated times of all activity paths leading to the particular event.

Step Six: Determining the critical path.

The critical path is the path with the following activities: A,C,D,F,U,H,I,K,L,M,N,O,P,Q,R,S,T and a duration of 29.64 weeks as shown in Figure 6. Visual Basic 6 program interfaces are shown in Figures 7 and 8.

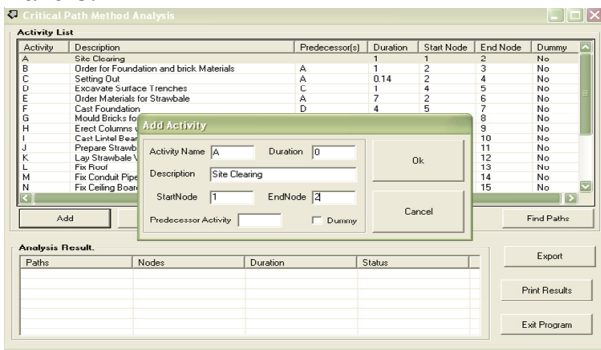


Figure 7. Activity input interface

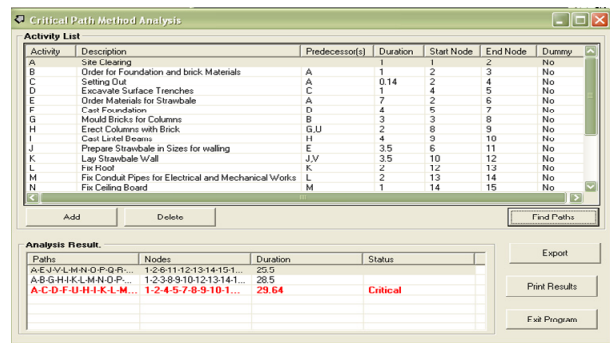


Figure 8. Activity output sample

Step Seven: - Constructing the Critical Path Network with Calendar Dates

With all the total time calculated, the first application of the Critical Path Analysis process was made simply by starting at the first event with a selected calendar date. Completion date at each event is based on the total time required to complete each event. Numerically and in reference to Figure 9, T=0 could be assumed as June 1 as a starting date as shown in Figure 10.

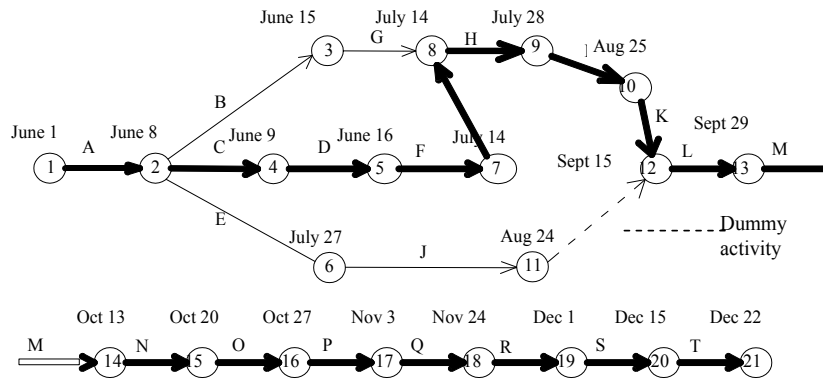


Figure 9. CPA network with dates substituted for Total times

Step Eight: - Economic Analysis

The cost of each activity and the possibility of spending more money to speed up the project (crash cost) were analyzed. The objective is to determine how quickly each activity can be completed and thus how long the whole project would take. The breakdown of cost for each activity is shown below and the summary presented in Table 7. The cost estimate is the sum of money for the individual items of work. The product of the quantities and the corresponding rates gives the amount. The computation of rates requires the knowledge of estimating. Theoretically, rate is specified as being equal to the summation of the cost of materials, labor, plant, the overhead and profit (Oyediran, 2006). Overhead and profit are included, if the project is to be handled by a contractor, however the rate presented below is for a direct labor contract. Equation (4) shows the relationship.

$$\text{Unit rate} = \sum Q_i + \sum L_i + \sum P_i + \sum O_i + \sum N_i \quad (4)$$

where: Q = Quantity, L = Labor, P = Plant, O = Overhead N = Profit. There are two main types of operatives on site who actually execute the work at site. They are: Artisans and Laborers/workmates. The minimum daily wage for artisans in Ilorin, based on eight hours working period is ₦1,500.00, while that of a labourer/workmate is ₦1,000.00. These figures are adopted for the calculation of the amount required (actual amount) for each element of work and are shown in Table 5. The analysis was carried

out based on the availability of more funds and the need to complete earlier than scheduled. A typical example of the analysis and result is presented in Figure 10. The results show the cost when the project is completed as scheduled and when it is crashed by one or more weeks.

Table 5. New program of work with the estimated cost

Activity	Description	Actual Duration (in weeks)	Crash Duration (in weeks)	Actual Amount (₺)	Crash Amount (₺)
A	Site Clearing	1	0.5	25,000	40,000
B	Order for Foundation and Bricks materials	1	0.5	387,600	407,600
C	Setting out of the building plan	0.14	0.07	8000	11000
D	Excavation of surface trenches for the strip foundation	1	0.5	24,000	32,000
E	Order Materials for Straw bale	7	6	25,000	30,000
F	Cast foundation and mould Bricks	4	3	33,000	43,000
G	Mould Bricks	3	2	15,000	20,000
H	Erect Brick Columns	2	1	13,000	15,000
I	Cast Lintel Beams	4	3	18,000	23,000
J	Prepare and stack straw bale in sizes	3.5	2	20,000	30,000
K	Lay Straw bale wall	3.5	2	65,000	75,000
L	Fix Roof	2	1	129,000	144,000
M	Fix conduit pipes for electrical and mechanical works	2	1	66,000	74,000
N	Fix Ceiling board	1	0.5	125,560	133,000
O	Floor Screeding	1	0.5	51,600	61,600
P	Fix Doors and Windows	1	0.5	121,000	136,000
Q	Plastering of the wall	3	2	131,000	156,000
R	Fix Electrical and Mechanical Accessories	1	0.5	36,000	51,000
S	Painting	2	1	57,000	67,000
T	Site Cleaning	1	0.5	8,000	10,500

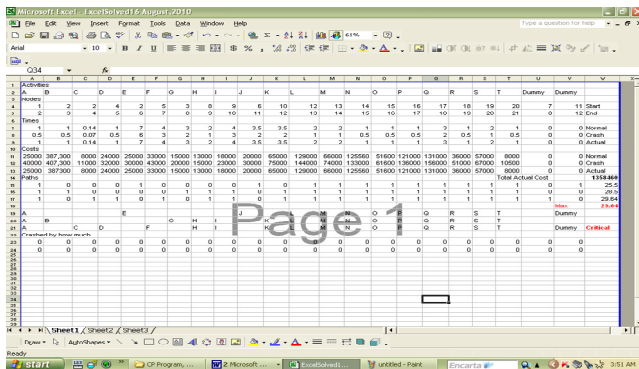


Figure 10. Excel output sample

But assuming the project is on contract, with a schedule completion time of 27.64 weeks and a penalty of ₺10,000.00 per week for being late, then the normal completion period of 29.64 weeks will attract a penalty of two weeks amounting to ₺20,000.00 making a total completion cost of: ₺1,358,460.00 + ₺ 20,000.00 = ₺1,378,460.00.

If the completion time is crashed by 1 week, the project takes 28.64 weeks and the penalty paid for the one week delay is ₺10,000.00, then the direct project cost is ₺1,360,460.00 and the addition of the penalty cost makes it ₺1,370,460.00, given a gain of ₺ 8,000.00.

Table 6. Summary of Crash result showing gain and loss

S/No	Description	Duration (weeks)	Amount (₺)	Gain (₺)	Loss (₺)
1	Normal time of Completion	29.64	1,378,460	-	-
2	Crashing by one week	28.64	1,370,460	8,000	-
3	Crashing by two week	27.64	1,365,460	13,000	-
4	Crashing by three week	26.64	1,371,293	7,167	-
5	Crashing by four week	25.64	1,377,960	500	-
6	Crashing by five week	24.64	1,385,960	-	7,500
7	Crashing by six week	23.64	1,395,960	-	17,500
8	Crashing by seven week	22.64	1,407,717	-	29,250

If the completion time is crashed by three weeks, the total project cost is ₺1,371,293.00, which is higher than crashing for two weeks thereby losing some money in the process. The law of diminishing returns is at work as is shown in Figure 8. Information regarding gain and loss are featured

DISCUSSION OF RESULTS

The activities A, C, D, F, U, H, I, K, L, M, N, O, P, Q, R, S, T with a duration of 29.64 weeks, are the activities along the critical path that must be completed on schedule, if the project completion time is to be maintained. A delay in the completion of any of the activities will cause a delay in the completion time. The total actual cost of the project is ₺1,358,460.00, if it is completed at a normal time of 29.64 weeks.

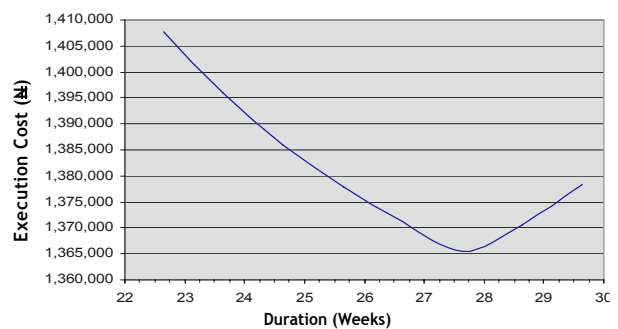


Figure 9. Cost/duration (Trend) curve for straw bale walled building

If the completion time is crashed by two weeks, no penalty is paid and the total project cost is ₺1,365,460 making a gain of ₺13,000.00, which is better than crashing for only a week.

in Table 7. Finally, crashing by two weeks is a better option, as it attracts a gain of ₦13,000.00 for the company.

The economics analysis of the three bedroom bungalow using straw bale wall shows that the total project cost is ₦1,358,460.00 with project duration of 29.64 weeks, while the use of sancrete blocks gave a total project cost of ₦1,753,460.00 and project duration of 28.64 weeks. The summary is shown in Table 7.

Table 7. Differences between using straw bale and conventional sancrete blocks

S/No	Material	Duration (weeks)	Amount (₦)	Difference (₦)
1	Straw bale	29.64	1,358,460.00	-
2	Conventional blocks (Control)	28.64	1,753,460.00	395,000.00

The differences in the use of straw bale and conventional sancrete block is significant because straw bale is a heap of dry stalk of grain product tied together with rope, which hitherto is referred to as waste and required no chemical processing, therefore, cost less, whereas sancrete block is a product of cement, sand and water. The cement constituent undergoes chemical processing, which in itself is cost intensive and therefore determines the eventual cost of sancrete block. The cost incurred when straw bale is used is for gathering of the straw and the tying into bales, while sancrete blocks are sold per unit.

❖ CONCLUSIONS

The outcome of past studies on compressive strength, vapour presence, moisture content and fire resistance of a straw bale wall has proven its suitability as a load bearing wall as well as a non-load bearing wall (infill). The information from the critical path analyses will aid in making a variety of decisions if the project planning, is faced in the beginning, with a negative slack on the critical path because of some forced contractual obligation, then the management will know immediately that some changes will be required in order to meet the required schedule. They will also know where the most critical of these changes are needed.

Available staff or resources from those events with surplus slack time might be shifted to more critical activities, new resources or staff assistance may be required to speed up certain activities.

Results of the economic analysis have shown that total actual cost of a three bedroom flat constructed in Ilorin with strawbale walls is ₦1,358,460.00 with a duration of 29 64 weeks. However, using a conventional sancrete block material instead of straw bale will increase cost to ₦1,753,460.00 with a duration of 28.64 weeks, thereby making a saving of one week project duration, but a loss in project cost totaling ₦395,000.00.

Critical path analysis is recommended for the formulation, scheduling, and managing the various milestones or activities in all construction work, as it provides an empirically constructed schedule of planning activities to meet some self-imposed or institutionally required calendar of events. It also provides a visual picture through the development of a model network displaying how all-planning functions tie together.

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