

Scheduling Linear Projects Using Ranked Positional Weights

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Construction projects are commonly scheduled using the critical path method with the assumption that resource provision is not restricted (i.e., no machine breakdown is assumed and there is no problem with labor supply). An easier method, called the positional weight method, for both unlimited and limited resources is presented. There is no need to determine the critical path, and hence the problems associated with determining total floats, slack time, and the like are no longer present. The method has been applied for scheduling assembly line manufacturing. Because there are similarities between assembly line manufacturing and construction projects, especially linear projects, the method can be applied to construction.

The conventional method for scheduling a construction project is to draw a network diagram for the activities and obtain the shortest duration using the critical path method (CPM). Scheduling of the works is then based on the critical path. The CPM method for scheduling is well established and is widely used in the construction industry. For easier application of the technique, various software, including Primavera and Timberline, are available. The positional weight technique is very much used for scheduling assembly lines in the manufacturing industry. There is much similarity between assembly line manufacturing and linear projects in the construction industry. Using the positional weight (which is the sum of the activity and all subsequent activity durations), the activities are assigned in accordance with the relative "heaviness" of the activities. To assist in the application of the method, a computer program has been written in GW-BASIC.

LINEAR PROJECTS

Many transportation projects (for example, highway tunnels) are linear in nature. In the construction of a highway tunnel, rock excavation is to proceed first. Subsequently, the walls of the tunnels are temporarily stabilized, and then the precast rings are installed or in situ concrete placed to form the permanent support for the excavated face. Laying of surfaces is usually done before the installation of the permanent support system. Construction of road pavement then proceeds, and finally, signaling, communication, lighting, and ventilation systems are installed. All these construction activities are linear in the sense that they all proceed in one direction. Such construction activity is also repetitive in nature. As in the case of tunnel construction, it is unlikely that excavation can be done in one operation (except for very short tunnels). Other-

wise, the unsupported length will be too long and tunnel collapse will be imminent. Even if temporary supports are provided, they will deteriorate and be rendered useless. More often the practical solution is to excavate a reasonable length by tunnel boring machine (TBM) or by drill and blast operation. The unsupported length often depends on the ground and groundwater regime. The excavated face is then protected by shotcrete/sprayed concrete. All the other work mentioned previously can then proceed sequentially. The whole operation is repeated for the next tunnel length. This process continues until the tunnel is complete. There is a need in this construction to determine the number of people and the types and number of machines that are required for each stage of the work. For example, what kind of TBM is to be used, and how many people and how many shifts are required to produce a reasonable length within a reasonable time frame? It is also necessary to determine how many spray concretors are required to provide the temporary protection. This process is repeated for all subsequent activities. Similar operations occur in other transportation projects—bridge, road, and railway line construction.

ASSEMBLY LINE MANUFACTURING

In assembly line manufacturing, workstations are assigned on a line. Assemblers or machines or robots at various workstations work on the line sequentially. A product is produced after it has been assembled from the first station until the last station.

RANKED POSITIONAL WEIGHT TECHNIQUE

One method, known as the ranked positional weight technique reported by Helgeson and Bernie (*1*), is used in assembly line balancing. Each work element is assigned a weight, which defines its position relative to the others in a descending order. The positional weight is the sum of the operating time required for that element and the times for all elements that must succeed that element. The elements are ranked in descending order in accordance with their positional weights. Once a desired production rate is determined, the cycle time can be calculated. This is the reciprocal of the production rate. The production rate is defined as the number of complete units produced over a period of time. The work elements are then assigned to workstations starting from the highest positional weight, subject to any precedence logic constraints. This means that a proper order must be followed for assem-

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bling the work elements. Work element assignment is carried out in such a manner that the cycle time is not exceeded by any workstation.

In addition to precedence constraints, there are technological and zoning constraints. Because of the specialized nature of certain work elements, it is necessary to assign them to particular workstations. This reflects the technological constraint. Because of interferences between work elements, it is desirable to separate the work elements on different workstations. This restriction is known as the zoning constraint.

TRADITIONAL METHOD OF RESOURCE LEVELING

In a traditional method of resource leveling, activities are assumed to be able to start as soon as possible in accordance with the precedence network. It is necessary to determine the critical path first. All activities that are not on the critical path have a certain degree of float, and it is possible to schedule them to begin at some later date. This permits noncritical activities to start at more convenient times, when the demands for resources are reduced. This process is known as resource scheduling.

To obtain an optimal solution to the scheduling problem, one has to resort to the techniques of operations research, such as linear programming and integer programming, among others. To schedule a construction project with hundreds of activities, high-speed computers with high memory storage capacity are required. Computing costs for solving such large problems are large. Instead of trying to obtain an optimal solution, some rules have been designed so that a close-to-optimal solution can be found while bypassing the computational difficulties. A set of these rules is called a heuristic.

There are many sets of heuristic rules. Some aim at minimizing the duration, and hence the cost and availability of the resource are of no consequence. Others minimize the duration of the project while restricting the level of resources. The first method is called unconstrained resource scheduling (URS), and the second is constrained resource scheduling (CRS).

Harris (2) describes the minimum moment algorithm, which is intended to consolidate various other heuristic methods into a workable method. It is a URS method, and thus the project duration is maintained. The argument for this approach is that in a construction project, the project duration is usually fixed, and only after the contract is awarded is the project manager faced with the problem of resource scheduling to reduce the manpower and machine requirements.

The method is based on a precedence network. It is assumed that activities cannot be split and that the resource rates are continuous throughout the duration of the activity. This algorithm uses an early start schedule derived from the CPM.

SIMILARITIES BETWEEN RESOURCE LEVELING AND ASSEMBLY LINE BALANCING

In resource leveling, the resource level for a particular activity is the number of workers required for the activity each day over the duration of the entire activity. In assembly line bal-

ancing, the operating time on each element is also a "resource" in the sense that it is a time assigned to the work element. From this approach, it can be seen that a work element is similar to an activity in resource scheduling because it requires resources.

A workstation in assembly line balancing is a fixed location where work elements are grouped together to be worked by an assembler. In construction, a project day also has a fixed location on a project time calendar where resources are required to perform the activity. A workstation is therefore similar to a project day.

In a construction project, certain activities may span several days. However, in assembly line balancing, it is not feasible for several workstations to be assigned to an assembler or work element simultaneously. This is the basic difference between the two processes. A work element in assembly line balancing occurs at only one station, but in resource scheduling, an activity may span several days.

In assembly line manufacturing (ALM), to avoid idling time in different workstations it is desirable to complete the portion of work in the same amount of time as other stations. In this way, there is no need for one station to wait for the other just because one station finishes the work much faster than the preceding station. To optimize resource allocation, it is necessary to assign different contents of work to each station so that all stations complete the work at the same rate as others. The overall production rate is the number of products produced over the time from the first workstation to the last.

In CRS of a construction project, the idea is to minimize the project duration and to allocate resources within the constraints.

In ALM, the cycle time (i.e., the time required for all workstations to complete the assembly work) is more or less constant. No workstation can exceed the cycle time. In CRS, a maximum amount of resources can be assigned on one day and may not be exceeded.

The required cycle time depends on the workstation with the longest operating time. This means that the cycle time cannot be less than the longest working time in any particular station. Because it is not always possible to maintain the same operating time for all stations, the best policy is to reduce the idling time by rearranging work contents in each station such that the operating time is about the same for all stations. As such in construction, the cycle time is equal to the maximum resource per unit time.

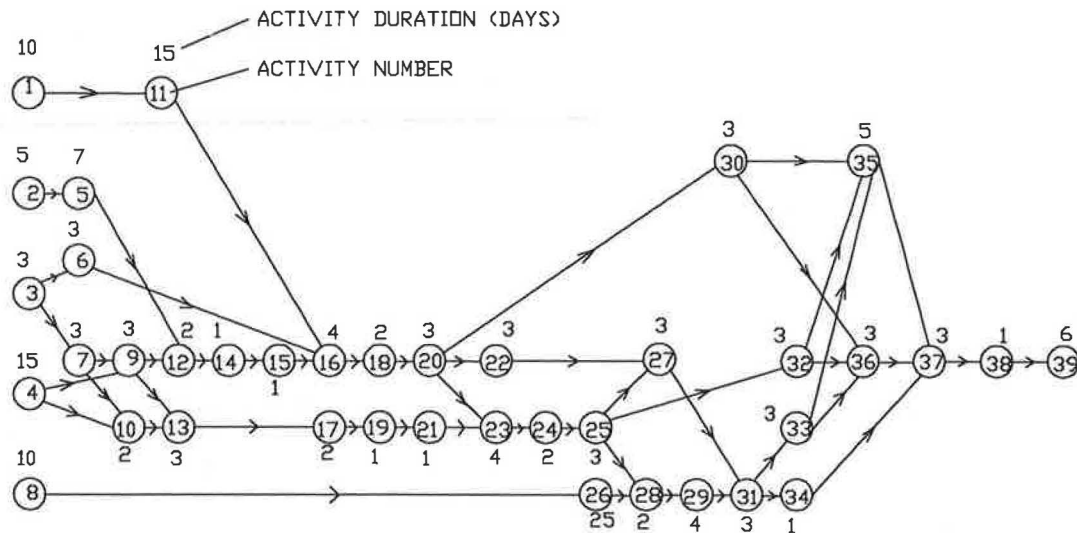
Kwartin (3) compared assembly line balancing and resource scheduling (see Table 1).

APPLICATION OF THE POSITIONAL WEIGHT METHOD TO LINEAR PROJECTS

Before the method is discussed, it is necessary to define "positional weight." The positional weight of an activity is defined as the sum of the duration of all succeeding activities. This is illustrated by considering an activity in the example project. Details of the project will be discussed later. In Figure 1, it can be seen that Activity 31 is followed by Activities 33, 34, 35, 36, 37, 38, and 39. The positional weight of the activity is equal to the duration of the activity itself plus the duration

TABLE 1 Comparison Between Assembly Line Balancing and Resource Scheduling (3)

Assembly Line Balancing	Resource Scheduling
Work element	Activity
Work element's time	Activity resource level
Work station	Project day
Maximum allowable work in any work station (cycle time)	Maximum level of resource per day

**FIGURE 1** Precedence network for bridge construction [based on Clough (4)].

of Activities 33 to 39. This is equal to 25 (3 + 3 + 1 + 5 + 3 + 3 + 1 + 6).

To apply the positional weight method (PWM), a precedence diagram, which should be similar to Figure 1, must be available. The positional weights are then ranked in descending order with the heaviest on the top. The following rules are applied:

1. The activity with the highest positional weight is selected and assigned on the first project day.
2. The unassigned resource per day is calculated by subtracting the assigned resource from the maximum available resource.
3. The activity with the next highest positional weight is then selected, and two checks are to be carried out: (a) An activity can only be assigned if all the preceding activities have been assigned (the preceding activities must be complete before the succeeding ones are assigned, and once an activity is started, it cannot be interrupted). (b) The resource requirement must be less than or equal to the unassigned resource available for the activity. If both (a) or (b) are met, then the activity is assigned to the day in question and Steps 2 and 3 are repeated for the activity with the next highest positional weight. If either of the conditions is not satisfied, that activity is bypassed and the activity with the next highest positional weight is selected and the two checks (a) and (b) are to be carried out.

4. Rules 2 and 3 are repeated for the same project day until at least one of the following conditions prevails: (a) the sum of the assigned resources equals the maximum resource level provided, (b) no more activities can be assigned because of precedence logic, or (c) all the remaining activities have resource requirements greater than the unassigned resources available.

5. The second project day is now considered. Any previously assigned activity cannot be interrupted, hence the resource for that activity is still needed. The activity with the next highest positional weight is then selected.

6. Rules 2, 3, 4, and 5 are then repeated until all activities have been assigned.

BRIDGE CONSTRUCTION PROJECT—EXAMPLE

To illustrate the principles described, it is desirable to consider an example project. The project described is contained in Clough (4).

A single-span vehicular bridge is to be erected over a small ravine. It is of composite steel-concrete construction and is of the deck-girder type. The bridge is supported by two reinforced concrete abutments. Each abutment consists of a breast wall and two wing walls and rests on twenty-eight 40-ft-long creosoted timber piles. The reinforced concrete paving slab is 10 in. thick and is supported by seven W 36 × 150 steel

floor girders. Concrete curb and aluminum guardrail are provided on each side. Exposed structural concrete is to receive a rubbed finish, and bridge surfaces are to be painted.

Figure 1 shows the network diagram. The activity descriptions are given in Table 2. The contents of work include mobilization, production of shop drawings, material delivery, excavation for abutments, driving piles, casting of footings, backfilling, installation of steel girders, casting of concrete deck, provision of guardrails, painting, cleanup, and final inspection. The project starts in June and ends in September, requiring a total of 70 days. One pile crew, five carpenters, seven ironworkers, four cement masons, two operating engineers, two truck drivers, and seven laborers are the maximum level of resource provided on any single day.

Most of the work is repetitive in nature. A large number of piles are to be driven, two abutments are to be constructed, seven steel floor girders are to be installed, and curb and guardrail are to be provided.

RESOURCE ALLOCATION USING PWM

Resource allocation for the bridge project is carried out using PWM. Resource allocation is carried out one by one. A resource level is first assumed. For example, it may be assumed that a maximum level of six laborers is to be provided. This number should be equal to or greater than the maximum resource requirement. For example, the maximum resource

TABLE 2 Description of Activities (4)

Act ¹	Dur ¹	Res ¹	Description
1	10		Produce shop drawings for abutment and deck reinforcement
2	5		Produce shop drawings for footing reinforcement
3	3		Moving in work area
4	15		Deliver foundation piles
5	7		Deliver footing reinforcement
6	3	4C,2L,1OE	Make formwork for abutments
7	3	2L,1OE	Excavate for abutment no. 1
8	10		Produce shop drawings for steel girders
9	3	1OE	Drive piles for abutment no. 1
10	2	2L,1OE	Excavate for abutment no. 2
11	15		Deliver abutment and deck reinforcement
12	2	2C,2L	Placing reinforcement and setting up forms for footing no. 1
13	3	1OE	Drive piles for abutment no. 2
14	1	3L	Pour concrete for footing no. 1
15	1	1C,2L	Strip formwork for footing no. 1
16	4	5C,4L,1OE	Placing reinforcement and setting up forms for abutment no. 1
17	2	2C,2L	Placing reinforcement and setting up forms for abutment no. 2
18	2	1C,6L,1OE	Pour concrete for abutment no. 1
19	1	3L	Pour concrete for footing no. 2
20	3	2C,4L	Strip formwork and cure abutment no. 1
21	1	1C,2L	Strip formwork for footing no. 2
22	3	3L,1OE	Backfilling abutment no. 1
23	4	5C,4L,1OE	Placing reinforcement and setting up forms for abutment no. 2
24	2	1C,6L,1OE	Pour concrete for abutment no. 2
25	3	2C,4L	Strip formwork and cure abutment no. 2
26	25		Deliver steel girders to site
27	3	3L,1OE	Backfilling abutment no. 2
28	2	1L,1OE	Placing steel girders
29	4	5C,4L,1OE	Placing steel and formwork for deck
30	3		Rub concrete surface for abutment no. 1
31	3	1C,6L,1OE	Pour concrete and cure for deck
32	3		Rub concrete surface for abutment no. 1
33	3	5C,6L,1OE	Stripping deck formwork
34	1	1L	Saw cut joints on deck
35	5	4L	Painting work
36	3		Install guard rails
37	3		Cleaning up
38	1		Final site inspection
39	6		Contingency for delays

¹Note:- Act: Activity; Dur: Duration (days); Res: Resource provided (no.); C: Carpenter; L: Laborer; OE: Operating Engineer.

requirement for laborers is six, and this is the minimum level to be provided. Once a resource level is decided, the procedure described for PWM can be applied. It is assumed that other resources are adequately provided so that the project is not delayed because of a shortage of other resources. A project duration and the daily resource requirement can be obtained using the PWM. This method is repeated for a higher level of resource so that a minimum project duration is achieved. After allocation of this resource is finished, allocation of other resources is carried out.

Step 1

Positional weight ranking is required. This is provided in Table 3. To apply Rule 1, Activity 4 is selected because the positional weight for that activity is the highest. The activity is assigned on the first day.

TABLE 3 Positional Weight Ranking

Activity Number	Positional Weight (Days)
4	92
3	86
1	86
7	80
2	77
11	76
9	75
5	72
8	66
12	65
6	64
14	63
15	62
16	61
18	57
26	56
20	55
10	55
13	53
17	50
19	48
21	47
23	46
24	42
25	40
28	31
22	31
29	29
27	28
31	25
33	21
32	21
30	21
35	15
36	13
34	11
37	10
38	7
39	6

Step 2

Following Rule 2, the unassigned resource per day is calculated. Because the maximum level of resource provided for the laborers is seven and the laborer requirement for Activity 4 is zero, the unassigned resource per day is 7 ($7 - 0$).

Step 3

In accordance with Rule 3, Activities 1 and 3 are both selected because they have the next highest positional weight (86 days). Before either is assigned, it is necessary to carry out the two checks.

Because there is no preceding activity for Activities 1 and 3, Rule 3a is met. The laborer requirement for both is zero. This is less than the unassigned resource ($7 > 0$). Conditions 3a and 3b are met, and Activities 1 and 3 are both assigned on the first day.

Steps 2 and 3 are then repeated for the activity with the next highest positional weight.

Activity 7 has the next highest positional weight (80 days). According to Condition 3a, preceding activity has to be completed before assignment can be considered. The preceding activity for Activity 7 is Activity 3. This activity has a duration of 3 days. Thus Condition 3a is not met, and Activity 7 cannot be assigned.

Activity 2 is now considered because it has the next highest positional weight (77 days). It can be seen that Conditions 3a and 3b are met by this activity, and this activity is also assigned on the first project day.

Activity 11 has the next highest positional weight (76 days), and this is considered. The preceding activity is Activity 1. Because the activity duration is 10 days, this activity is not yet finished and according to Condition 3a cannot be assigned. Similarly, Activities 9 and 5 cannot be assigned.

Activity 8, which has the next highest positional weight (66 days), is now considered. Conditions 3a and 3b are met, so this activity is assigned. Up until now, Activities 4, 3, 1, 2, and 8 have been assigned. Because of Condition 3a, no more activity can be assigned until after 3 days, the duration of Activity 3.

Step 4

The fourth day is now considered. Activity 7 is considered because it has the highest positional weight (80 days). Condition 3a is met, and because Activity 7 requires two laborers, which is less than seven, this activity is assigned. Similar reasoning applies for Activity 6, and there is a surplus of three laborers.

Step 5

The earliest date an activity can be assigned is Day 6, because Activity 2 finishes on Day 5. Activity 5 is assigned because conditions 3a and 3b are met. No other activities can be assigned on this day because of precedence logic. The foregoing

procedure is repeated for other activities. The order in which the activities are assigned is given in Table 4.

RESULTS

Using AssemBalance, which is a computer program based on PWM for resource allocation, resource requirements and project duration are obtained. This solution is also possible by hand calculation, which is neither complicated nor difficult to apply.

The minimum project duration is 70 days. The minimum levels of resource required are five carpenters, seven laborers, and two operating engineers. This is better than the solution reported by Clough (4), which required six carpenters instead of five, seven laborers, and two operating engineers, for the same project duration. The solution was obtained using CPM. Because the minimum requirement for various activities is five, the level cannot be reduced any further. PWM is superior and easier to use, and resource usage is minimized.

TABLE 4 Order of Activity Assignment

Order of Assignment	Activity Number
1	4
2	3
3	1
4	2
5	8
6	7
7	6
8	5
9	11
10	26
11	9
12	10
13	12
14	13
15	14
16	15
17	17
18	19
19	21
20	16
21	18
22	20
23	23
24	22
25	30
26	24
25	25
26	28
27	27
28	32
29	29
30	31
31	33
34	34
35	35
36	36
37	37
38	38
39	39

The duration of a project is affected by the level of resource provided. In the case of laborers, reducing the number by one increases the project duration by 4 days. It is not possible to reduce the number of carpenters any further, as explained. Reducing the number of operating engineers by one increases the duration of the project by 3 days.

Increasing the work force from 5, 7, and 2 for carpenters, laborers, and operating engineers, respectively, to a higher level, even up to 20 for each trade, does not reduce the project duration any further. The minimum project duration is still 70 days. This is the critical path duration.

A bar chart showing the resource requirement and start day and finish dates for the resources is shown in Figure 2.

ASSEMBALANCE

AssemBalance is written in GW-BASIC Version 3.20, which is one of the most popular engineering computer languages. BASIC is perhaps the cheapest computer language package obtainable and is readily available to personal computer users. There is no need to purchase other software (other than a BASIC package) to run AssemBalance. This fact should enable AssemBalance to be more widely applicable.

Other project management programs based on CPM are available. In general, they are more difficult to use, partly because of the complexity of the CPM technique itself.

AssemBalance is user interactive. The software allows easy inputting. In case mistakes are entered, the program provides opportunities for corrections.

DISCUSSION OF RESULTS

PWM is extremely easy to apply, and it provides solutions not only to a URS problem but also to a CRS problem. There is no need to first determine a critical path. These are excellent advantages.

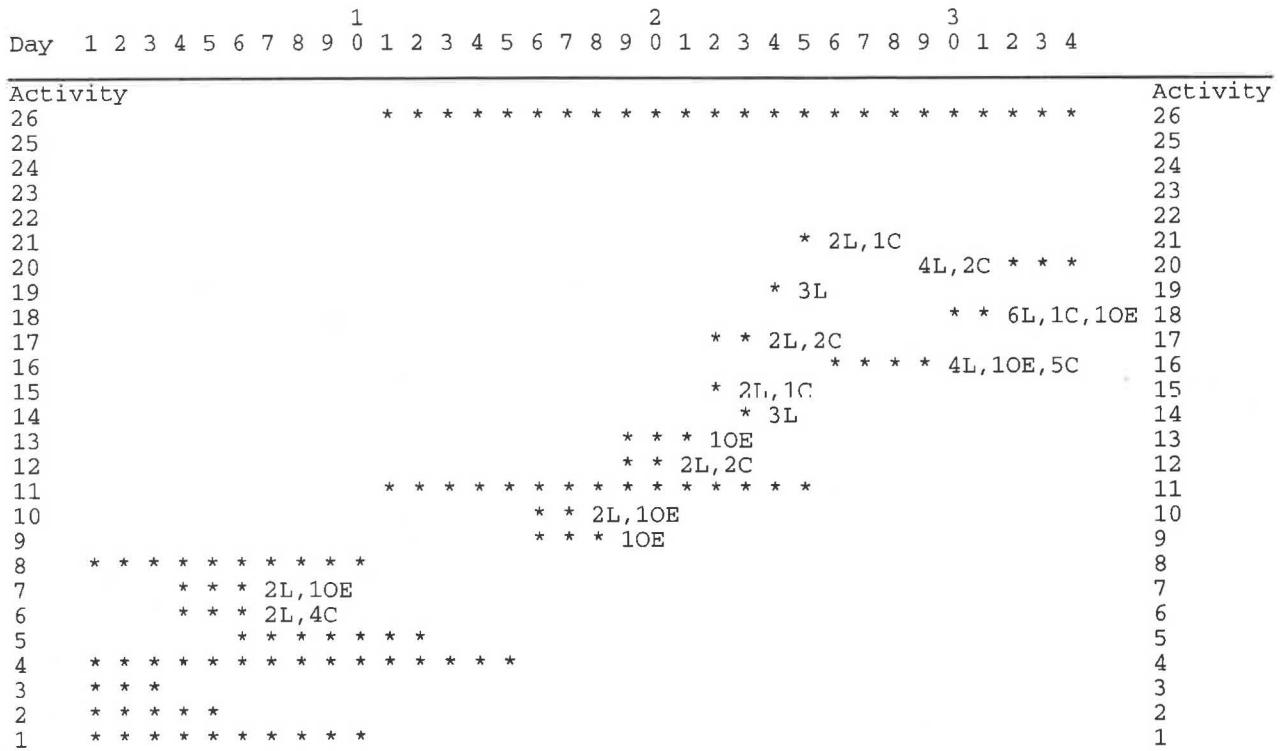
A better solution is possible with this method than with CPM. Instead of six carpenters, only five are needed without delaying the project, thus saving project expenses.

Compared with linear programming, this method requires little computational effort. There is no need to set up an objective function and resource constraint equations. Hence, another computational difficulty is avoided. Furthermore, PWM produces a critical path as a by-product.

The solution obtained is relatively robust in the sense that even if a mistake is made, a good solution is still possible. For example, if the positional weight for Activity 37 is miscalculated, the final solution is still the same. This is because PWM depends not only on the positional weight but also on the precedence logic.

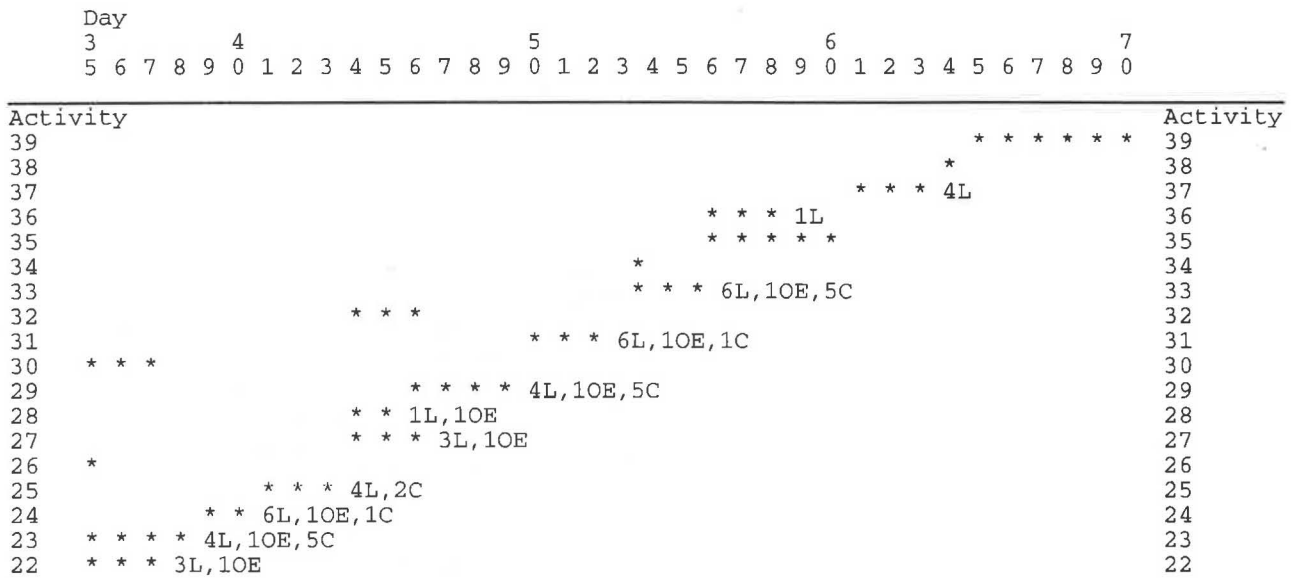
CONCLUSION

The example indicates that assembly line balancing can be of great value to the scheduling of highway and other projects. The method is simple, and there is no need to get into the complexity of obtaining the critical path.



LEGEND: * * * 2L,1OE,4C - 2 LABORERS, 1 OPERATING ENGINEERS AND 4 CARPENTERS ARE REQUIRED FOR THREE DAYS (ONE ASTERISK REPRESENTS ONE DAY)

(a)



LEGEND: * * * 2L,1OE,4C - 2 LABORERS, 1 OPERATING ENGINEERS AND 4 CARPENTERS ARE REQUIRED FOR THREE DAYS (ONE ASTERISK REPRESENTS ONE DAY).

NOTE: WHERE RESOURCES ARE NOT INDICATED, IT IS EITHER (1) NO RESOURCES ARE REQUIRED (FOR EXAMPLE, CONTINGENCY FOR DELAY) OR (2) ANALYSIS HAS NOT BEEN PERFORMED ON THAT PARTICULAR ACTIVITY (ONLY THREE TYPES OF RESOURCES ARE CONSIDERED FOR THE PURPOSE OF ILLUSTRATION).

(b) IN THE CASE OF (2), UNCONSTRAINED RESOURCE IS ASSUMED.

FIGURE 2 Bar chart showing resource requirement and activity start and finish dates: a, Days 1 to 34; b, Days 35 to 70.

Much computational time can be saved and human errors can be reduced because the method is much simpler to apply. Because there is no special machine requirement, PWM can be successfully applied on site. The content of the work is likely to be changed because of design variations and unforeseen ground conditions, so modification of the precedence network is also necessary. Using PWM, the project duration and resource requirement can again be obtained readily.

An unexpected outcome of this method is that a critical path can be obtained as a by-product. Thus, this method is of importance not only to resource scheduling but also to project planning.

PWM can be used to solve both constrained and unconstrained resource allocating problems. The capability is of great use to resource planning because both problems are likely to occur in construction.

AssemBalance is easy to use and is user interactive. Little input information is required to run the program. The program is written on GW-BASIC, so the software required to run the program is minimal. There is also little machine dependence, because the program can be run on an IBM PC.

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