Managing Resource Leveling

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Introduction

At last year's AACEi Annual Meeting, two presentations concerning CPM scheduling were given challenging the notion that total float values should be used as the sole yardstick for measuring delay on a construction project. While "automatic resource-leveling" functions offered by scheduling software applications were intended to incorporate resource requirements into the scheduling process, the software's inability to calculate accurate total float values when leveling has precluded their use for specified contractual requirements.

As a result of this failure, contractors have utilized a manual method of adding "preferential logic" as a means of reflecting resource constraints while calculating accurate total float values. Instead of solving the resource problem, however, the result is often inaccurate schedules produced by already overtaxed project engineers who don't have the time to revise preferential logic to correct the "out-of-sequence progress" that inevitably results.

This paper will review the concept and benefits of automatic resource-leveling, and will examine a recent software application developed by one of the authors that has managed to bridge the gap between automatic resource-leveling and manual preferential logic. Also considered are the documentation requirements necessary to allow the owner to understand and believe the resource leveling output. The result is a versatile schedule able to be used in "what-if scenarios" as well as a contract submittal capable of conforming to the total float requirements of scheduling specifications.

Critical Path Method Scheduling

Critical Path Method (CPM) is a mathematical method for analyzing a network of logically-connected activities to determine the overall duration of the project (the "critical path"). It provides an indication of how long "non-critical" activities can be delayed before impacting the overall duration of the project, based on their "total float" values. Because CPM is used in construction litigation for quantifying delays as a cause of monetary damages, correct computation of total float is both essential and problematic, and can involve millions of dollars for every day that is affected.

Total Float (float) is calculated as the latest allowable finish of an activity minus the earliest allowable finish (LF – EF) or the latest allowable start minus the earliest allowable start (EF – ES). In application, float denotes the amount of time that an activity path is away from the late finish of a project--it can be 0, positive, or negative in value based on this relationship.

Currently, float analysis is the method used in the construction industry to measure activity delays and determine when they become project delays. A typical contract specification is quoted below:

> *"Time extensions will be granted only to the extent that demonstrated time adjustments for the activity or activities affected* ***exceed the total or remaining float along the critical path*** *of activities at the time of actual delay or change order work performance."*

"Exceed the total or remaining float along the critical path" is bolded to emphasize the importance of total float values in contractually demonstrating delay. Without float analysis, most contracts would have no formalized method for awarding time extensions.

CPM Schedule Logic

To understand float, one needs to first understand CPM logic. There are two types of logic, "physical" and "preferential" logic. Physical logic is sometimes called 'hard logic' and reflects the dependencies that two different activities have to each other based upon the inherent nature of the work being performed. An example may be forming and pouring concrete. The forms first must be complete before the concrete can be poured.

Preferential logic is also sometimes called 'soft logic'—it reflects dependencies that are defined by the project management team where a specific sequence of activities is preferred, but not mandatory. An example of preferential logic is resource- or phase-related sequencing of project work elements.

Both types of logic are equally appropriate in a CPM schedule for it to effectively model a construction contractor's plan for completing a construction project successfully.

Where physical and preferential logic are basic CPM scheduling terminology, software manufacturers have added some terms to describe how a CPM schedule is impacted by changes in the field. Specifically, Primavera Systems defines "out-of-sequence progress" as work completed for an activity before it is logically scheduled to occur. An example is a successor activity in a finish-to-start relationship that starts before its predecessor is completed (see Figure 1 below).

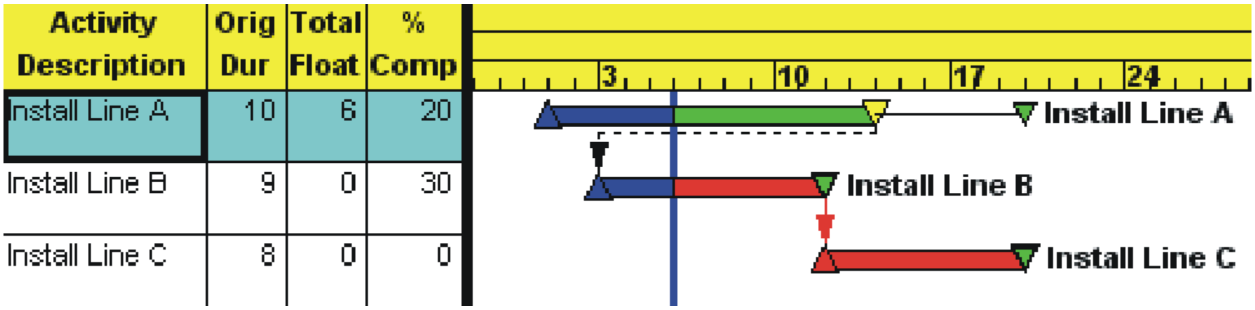

Figure 1: Out-of-Sequence Progress.

Because physical logic relationships are for the most part inflexible, out-of-sequence progress is most often the result of statusing a schedule that contains preferential logic. As stated above, preferential logic is often used to "stagger" activities using the same resource that are otherwise independent in terms of physical logic. If a problem arises during the execution of one such activity, contractors may shift their workforce over to the next activity while the delay to the first is being mitigated. Since the work is mostly independent, this shifting of resources may not have an impact on the rate of work progress.

In a case such as this, however, the CPM will show that the contractor is not working in accordance with the originally planned work sequence. Primavera Project Planner (P3), which is widely recognized as the CPM scheduling software of choice in the construction industry in the United States, has two different calculation modes designed to deal with this issue, "retained logic" and "progress override."

Retained logic mode causes P3 to not schedule the remaining duration of a progressed activity until all of its predecessors are complete. In effect, P3 suspends the activity until all predecessors have been completed. This is the default CPM calculation mode for P3 and generally recommended by construction managers and project owners in an effort to ensure that successive updates "retain" the logic of the approved baseline schedule. Many critics, however, argue that the use of retained logic results in a too pessimistic appraisal of schedule progress, since it doesn't reflect the inherent presence of change in a construction project.

Conversely, progress override mode allows the activity that started out-of-sequence to progress without delay. In other words, once an activity has started, the program will ignore any predecessor work not completed and act as if the out-of-sequence activity can continue making progress without impact.[(1)] It effectively breaks the logic tie, which in many cases creates an "open end" in the network. Progress override was invented, in part, to try to overcome the effects of out-of-sequence progress on a schedule with retained logic. Where retained logic is thought to be too pessimistic, progress override is likewise criticized for its overly optimistic estimate of progress.

[(1)] A third CPM calculation mode is offered with Primavera's new P3e/c software called "actual dates." Actual dates mode acts like retained logic for activities started out-of-sequence but like progress override for activities that also finish out-of-sequence.

Resource Loading

Resource loading and leveling is an excellent technique to use in attempting to overcome the problems created through the combination of retained logic and out-of-sequence progress. Before you can "level" a schedule, however, the resource requirements for each activity must be defined and "loaded." Activity resources are general categories of labor and/or equipment that are needed to accomplish the required work. The total daily requirement for any particular resource is computed by subtotaling the resource loading from all activities scheduled that day. This resource profile can then be utilized to define the daily resource staffing levels required.

Resource Leveling

The significance of resource loading is that it underscores the fundamental interdependencies between construction activities and resources under which they will be performed. Resource leveling goes a step further and actually adjusts a CPM's calculated early dates based upon resource availability. It analyzes the resource needs of an entire project and attempts to minimize problems associated with insufficient quantities and/or fluctuations in resource demand on a day-to-day basis. There are two types of resource leveling, "time-constrained" and "resource-constrained".

Time-constrained leveling works under the assumption that the project must be finished by a certain time, using as few resources as possible. Since time (not resource usage), is critical, the project will not be allowed to be delayed. Conversely, resource-constrained leveling begins at the status date and works forward to project completion, distributing activities over time based upon both logic and resource availability. This technique recognizes that the project must be finished as soon as possible, but not without exceeding some specific level of resource usage. In other words, this method will allow the project to be delayed past its early finish date if the resources required to finish on time are not available.

Assuming that a contractor is performing the scheduling, the method of resource leveling selected should be based on "entitlement" in terms of a potential time adjustment. If the contractor has not experienced an excusable delay, time-constrained leveling should be used in order to maintain the contractual completion date. However, if the contractor has been delayed for reasons "outside of their control," resource-constrained leveling will prevent the occurrence of resource over-allocations and most likely will result in a delay to project completion. The period of time between the contractual completion date and the delayed completion date will then be the amount of time extension that the contractor should ultimately seek from the owner.

Manual Leveling

Regardless of the type of constraint, there are two techniques for applying resource leveling—"manual" and "automatic". Manual leveling has been utilized in some form or fashion since the start of CPM. Starting in 1986, however, Primavera revolutionized the resource leveling paradigm with their built-in automatic resource leveling capability. The user is able to define several "heuristics," [2] or rules that are used by the software to decide in a split second which activities should or should not be delayed due to resource over-allocation. An example of leveling heuristics would be to schedule activities loaded with the same resource first by early start, then by the least amount of total float in order to minimize any resulting delay to the critical path.

The major drawback associated with automatic resource leveling, however, is realized when the practice is applied to a contractually-specified CPM schedule submittal. Because there are no logic ties connecting the activities that have been leveled, the "backward pass" is not able to accurately calculate late dates for the leveled activities. As a result, leveled activities are shown to have float values that are not representative of their true criticality. Considering our earlier discussion regarding the importance that most construction contracts place on total float values in assessing the impact of delay, one can see why the practice has yet to gain acceptance beyond an internal "what-if" experiment.

Manual leveling, on the other hand, involves using preferential logic to stagger resource-constrained activities. The advantage of this technique is that float values are reflective of critical/near-critical status of leveled activities, since an accurate forward and backward pass can be achieved for the entire schedule. For this reason, most contractors elect to use manual resource leveling to describe their resource plan in accordance with contractually specified requirements. The major drawbacks in using this method are the significant amount of time required to manually level the baseline schedule, as well as the high level of maintenance required to correct the out-of-sequence progress that will no doubt occur as an element of periodic updating.

The next section of this paper demonstrates the principles of resource leveling and why automatic leveling should be the preferred solution for out-of-sequence progress. Our sample project represents a summary level CPM schedule for the construction of a generic treatment plant (Figure 2 below), which is 7 months in overall duration.

[2] Heuristics are a given set of conditions that leads to a useable solution. Note that this does not guarantee the optimum setting, only that it is likely to lead to a useable one.

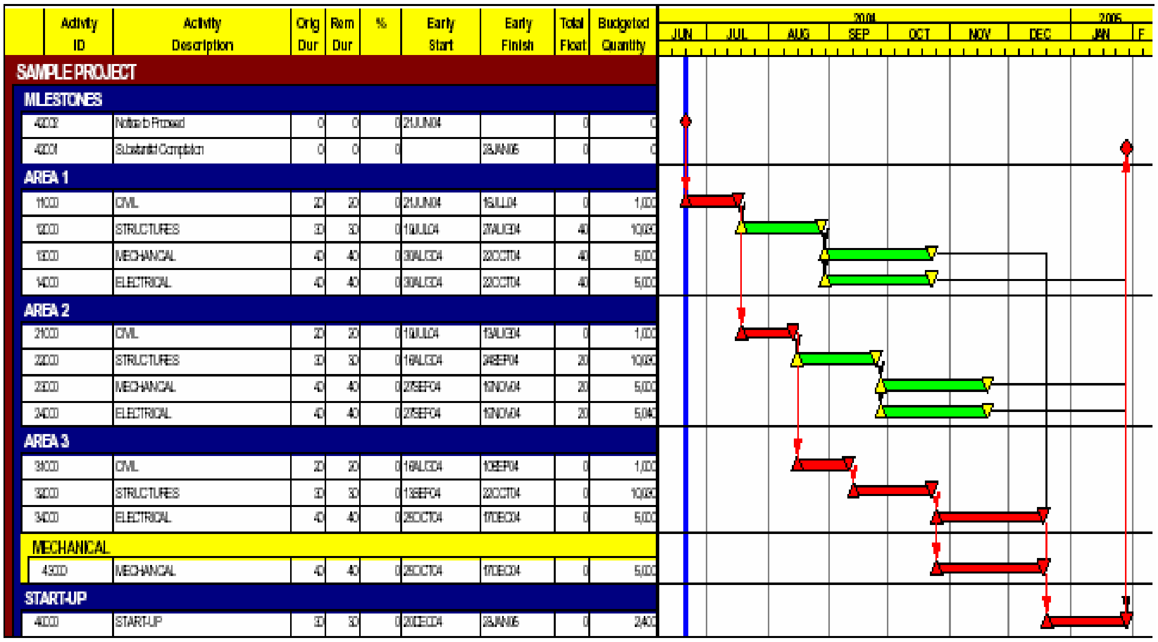

Figure 2: CPM schedule for sample project.

It is organized by 3 work areas and Start-up as the first level of the project's WBS (which is how the project will be managed), then by discipline as the second level. Each activity is loaded with budgeted labor-hours (as shown in the far right column of Figure 2.) Minimal preferential logic is used in civil activities only to reflect the contractor's intended phasing plan of moving from area 1 to 2 to 3 (start-up is a successor to all three areas). All other logic is physical logic only. No end-date constraints have been assigned yet, so the critical path (shown in red) reflects a total float of 0.

Notice the electrical and mechanical installation are planned to be concurrent within each of the three areas—we will further define the mechanical activity in Area 3, while leaving the electrical at a more summary level. The assumption in this example is that the mechanical summary activities reflect the installation of above ground piping, which in Area 3 will be comprised of five different lines, labeled Line A through E. The installation of these lines are essentially independent, other than for the fact that the contractor only has planned for one mechanical crew to be working in Area 3 at any given time.

Individual time estimates were made based on the labor-hours budgeted for the installation of each of the five lines in Area 3, and the resulting activities were added to the schedule to replace the original 40-day summary activity. Work on each of these activities cannot begin until the structures work in Area 3 is complete, so we add a finish-to-start relationship from Activity 32000, "Structures," to each of our five new activities. "Start-up" cannot begin until each mechanical activity is complete, so a physical logic tie is added from each of the line installation activities to Activity 40000.

As stated earlier, even though the five mechanical activities are essentially independent, our contractor has planned for one mechanical crew to working in Area 3. Since the physical logic relationships incorrectly suggest that the contractor is able to install each line concurrently, preferential logic will be added to schedule this work in the planned sequence. Since the plan is to first install the lines with the greatest amount of budgeted labor-hours, preferential finish-to-start relationships are added from Install Line A to Install Line B, from B to C, C to D, and D to E (Figure 3 below). Notice that the total float values for each of the mechanical activities in Area 3 are still zero, correctly reflecting that they are on the critical path to complete the project. A delay to any of these activities will result in a delay to the entire project.

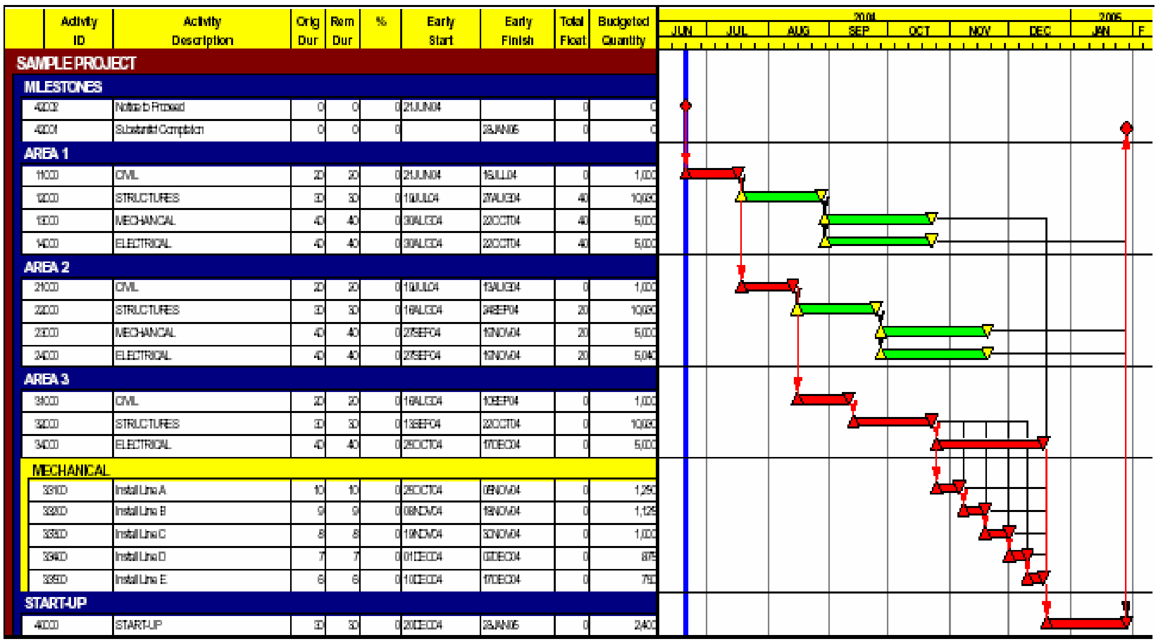

Figure 3: Preferential logic for Area 3 mechanical activities.

Limits are now set for each discipline's labor-hours/day to be worked in each area, so that P3's resource profiling can be used to graphically identify resource over-allocations specific to an individual area. For Area 3 mechanical, "Normal Level" is set to 125 labor-hours/day, or 15 full time equivalent workers (FTE's) per day. The "Maximum Level" is set to 150/day, or 18 FTE's per day, to account for a certain amount of "incidental overtime" that is to be experienced on any project The "Resource Profile" histogram at the bottom of Figure 4 reflects that the labor-hours for Area 3 mechanical activities do not exceed the normal limit of 125 hours/day, or 15 workers, at any time during the two-month period that they will be performed.

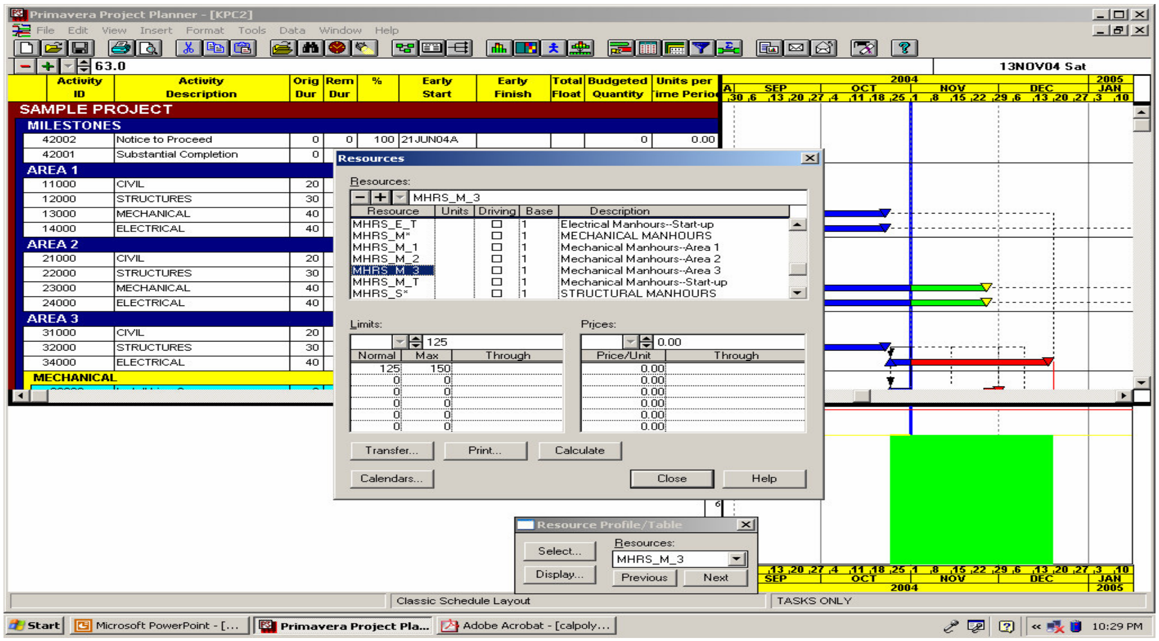

Figure 4: Setting limits for mechanical labor-hours.

As stated previously, it is only when a CPM schedule is statused with actual progress that out-of-sequence problems arise. Figure 5 below reflects a schedule update after 4 months worth of "as-planned" progress—accordingly, there has been no out-of-sequence progress as of yet. Notice that the Area 3 mechanical activities detailed earlier are ready to commence.

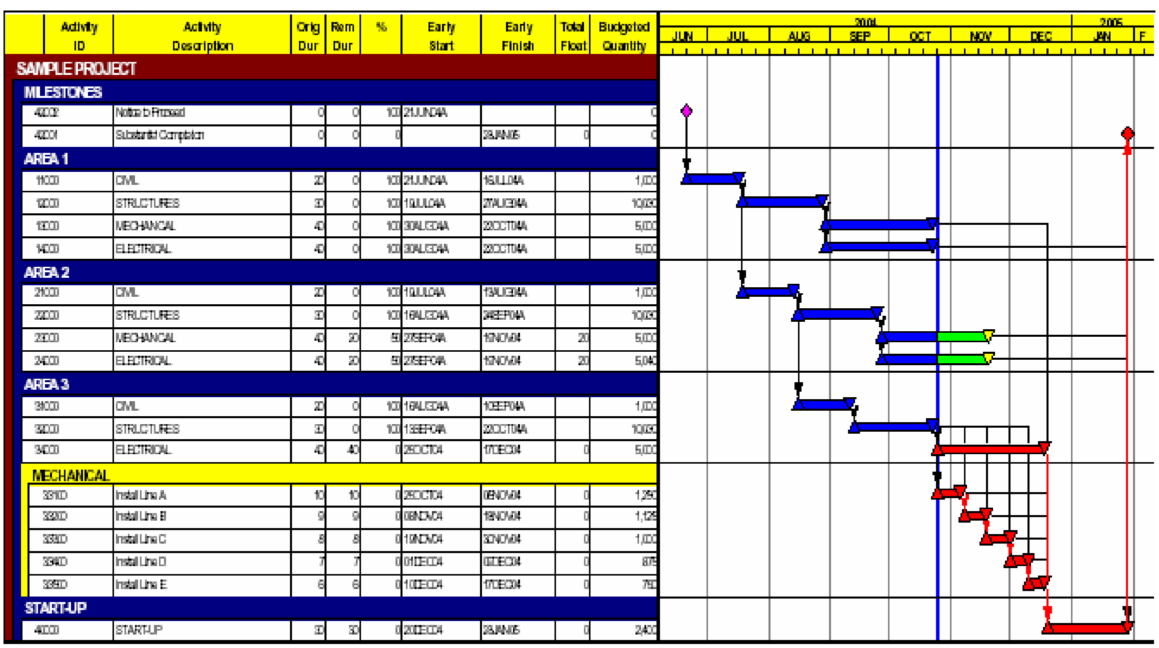

Figure 5: CPM update prior to start of Area 3 mechanical.

The update shown in Figure 6 now reflects an additional week of progress. For whatever reason (access restrictions, lack of materials, etc.), the various mechanical activities are not being carried out in the 'preferred' sequence, which happened to be alphabetically from A through E. Instead, installation of Line C has begun first (now at 50%) while Line A has not yet started.

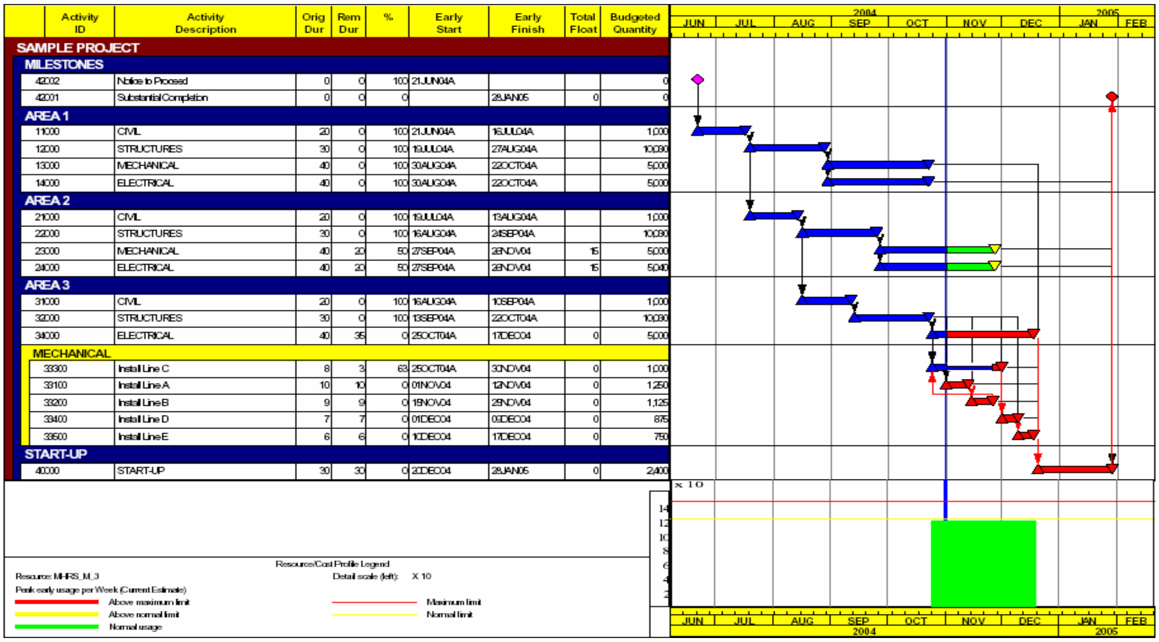

Figure 6: Weekly update with retained logic.

The example above shows what such a schedule would look like using P3's Retained Logic calculation mode to account for this out-of-sequence progress. The all-green histogram shows that the contractor is still meeting his planned resource utilization (yellow line is normal limit of 125 labor-hours/day). The float values of these activities are still 0, which still accurate reflect their critical status.

The problem with retained logic is illustrated graphically by the "necked" activity bar for the remaining duration of Line C, which indicates that the work for that activity will not resume until the completion of Line B (the original planned sequence.) This is not correct, however, since these activities are essentially independent. Once any of the mechanical activities are started, it can be reasonably expected that the work on that activity can and will continue until completion. In this instance, the retained logic CPM calculation mode is not reflective of reality.

As discussed earlier, it could be argued that P3's Progress Override CPM calculation mode would be more appropriate in this instance. Figure 7 shows the same schedule update with the CPM recomputed using progress override, which realistically assumes that once an activity starts with out-of-sequence progress, it can continue uninterrupted.

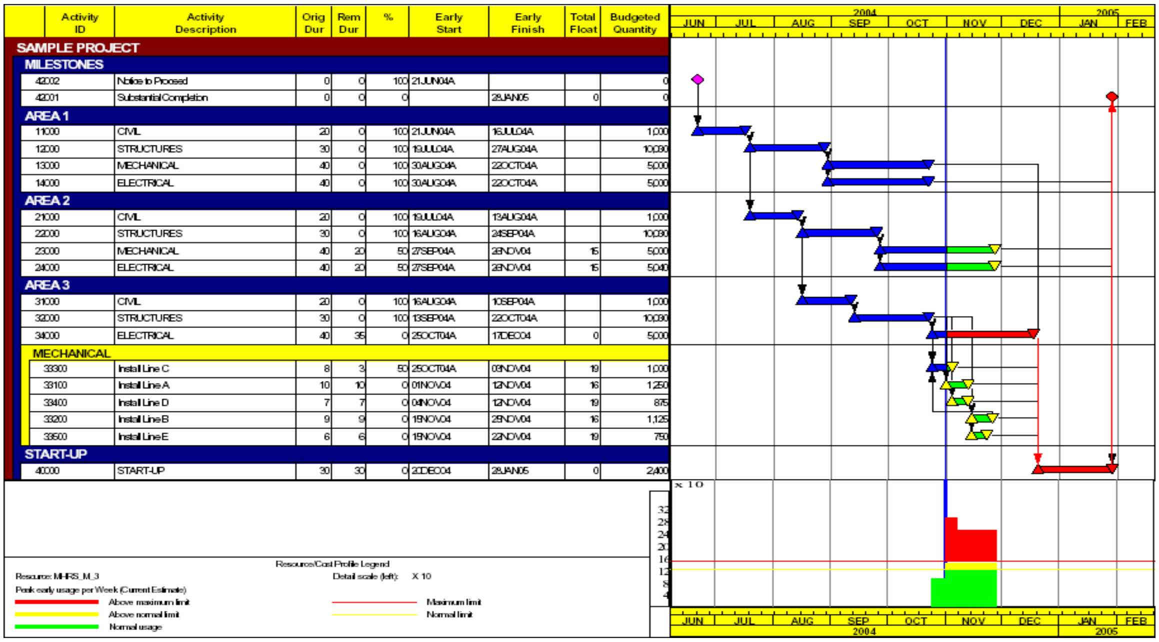

Figure 7: Weekly update with progress override.

As you can see, the original sequence of Line A through E has been broken, since the software assumes that the finish-to-start tie between Line B and C was not accurate (even though the software still draws the relationship between the two). As a result, Lines C, A, and D are now shown to be concurrent, followed by Lines B and E (also shown to be concurrent). The red in the corresponding resource histogram shows that this sequence exceeds the upper limit of 150 labor-hours/day.

Since the contractor has yet to revise its resource plan that called for a maximum of 18 mechanical workers in Area 3 at any given time, this schedule is not currently achievable. In addition, Area 3 mechanical activities now show they are no longer critical in terms of total float since they are being completed sooner than originally scheduled. This is not accurate, however, since the shorter overall duration has been shown to be unachievable based on the contractor's resource plan.

Before the problem of out-of-sequence progress can be effectively addressed, it must first be recognized. Although the necking illustrated above helps to identify out-of-sequence progress graphically, P3 also generates a report when it calculates the CPM schedule that lists out-of-sequence progress (regardless of whether retained logic or progress override has been utilized).

To some project owners, any out-of-sequence progress listed in the scheduling report is perceived as a "red flag" that reflects problems with the contractor's schedule. These owners require that the preferential logic that caused the out-of-sequence progress be corrected before they will approve a periodic update. In effect, they require that the schedule logic be "as-built" to reflect that way the project is actually progressing in the field. As we discussed previously, a contractor should also aspire to correct out-of-sequence progress to ensure that the remaining activities are representative of the current resource plan.

To correct the out-of-sequence progress occurring in the sample project examined thus far, a contractor would typically perform a more focused type of manual resource leveling specifically directed at those activities that have been started out of their original sequence. The preferential logic would be deleted from A to B and from B to C and added as relationships from B to A and A to C This 17 activity summary schedule required four logic changes to correct a relatively simple example of realistic progress. It isn't difficult then to imagine how this manual leveling process can become extremely time-prohibitive to perform each month on a detailed construction schedule that may contain thousands of activities. Luckily, P3's automatic leveling is specifically designed to address this problem, thereby adding a certain degree of flexibility back into the construction scheduling process.

If automatic resource leveling is going to be used effectively, it needs to be incorporated into the baseline schedule from the beginning. In Figure 8, the sample schedule is again shown in a baseline status (no progress), with the same basic logic ties as originally discussed (preferential logic between Area civil activities only).

Activity ID	Activity Description	Orig Dur	Rem Dur	%	Early Start	Early Finish	Total Float	Budgeted Quantity
SAMPLE PROJECT								
MILESTONES								
42002	Notice to Proceed	0	0	0	21JUN04		0	0
42001	Substantial Completion	0	0	0		28JAN05	0	0
AREA 1								
11000	CIVIL	20	20	0	21JUN04	16JUL04	0	1,000
12000	STRUCTURES	30	30	0	19JUL04	27AUG04	40	10,080
13000	MECHANICAL	40	40	0	30AUG04	22OCT04	40	5,000
14000	ELECTRICAL	40	40	0	30AUG04	22OCT04	40	5,000
AREA 2								
21000	CIVIL	20	20	0	19JUL04	13AUG04	0	1,000
22000	STRUCTURES	30	30	0	16AUG04	24SEP04	20	10,080
23000	MECHANICAL	40	40	0	27SEP04	19NOV04	20	5,000
24000	ELECTRICAL	40	40	0	27SEP04	19NOV04	20	5,040
AREA 3								
31000	CIVIL	20	20	0	16AUG04	10SEP04	0	1,000
32000	STRUCTURES	30	30	0	13SEP04	22OCT04	0	10,080
34000	ELECTRICAL	40	40	0	25OCT04	17DEC04	0	5,000
MECHANICAL								
33100	Install Line A	10	10	0	25OCT04	08NOV04	30	1,250
33200	Install Line B	9	9	0	09NOV04	19NOV04	21	1,125
33300	Install Line C	8	8	0	19NOV04	30NOV04	13	1,000
33400	Install Line D	7	7	0	01DEC04	09DEC04	6	875
33500	Install Line E	6	6	0	10DEC04	17DEC04	0	750
START-UP								
40000	START-UP	30	30	0	20DEC04	28JAN05	0	2,400

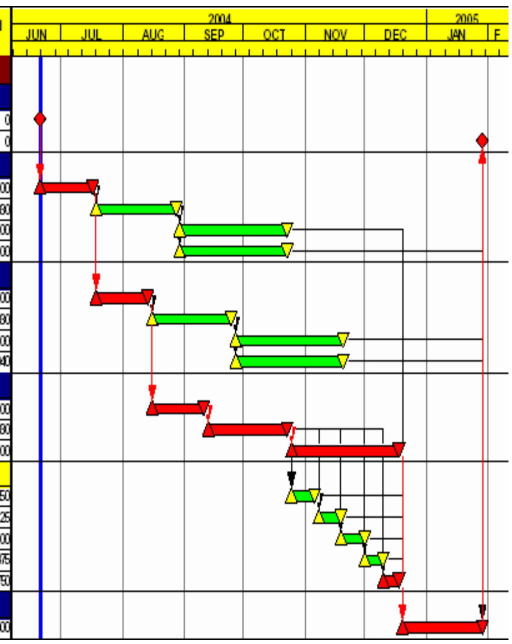

Figure 8: Automatically leveled CPM.

Since Area 3 Mechanical labor-hours are the resource we examined earlier, they have been selected as the resource to be automatically leveled in this example. The heuristics used were to give priority to activities based upon their early finish first, then least amount of total float. Because the goal at this point in the baseline process is to produce the best estimate of project duration based on the resource plan, resource-constrained leveling has been utilized.

The initial result of the automatic leveling in terms of the overall project duration still reflects a project duration of 7 months. In addition, because the mechanical activity durations are representative of their budgeted labor-hours (decreasing from A through E), their total float values based on physical logic result in the same line sequence that was originally derived with preferential logic.

For example, Activity 33100 (Install Line A), with an original duration of 30 working days, would have less total float than Activity 33200, (Install Line B), with a duration of 21 days. Since physical logic alone results in these activities being concurrent (the same early start date), the activity with the least total float (Install Line A) is scheduled to occur first.

The fact that these five mechanical activities still control the project's overall duration has not changed, since a delay to any of them will delay the entire project. The first indication that there is a problem, however, lies in the fact that only Activity 33600 (Install Line E) is colored red to graphically reflect its criticality. A closer inspection of the other four activities' total float values reveal that they are not only greater than 0 (non-critical), but also that they all are different. This is inconsistent with specification requirements discussed earlier, since there is no longer a consistent critical "path" in terms of float values. Without consistent (and correct) total float values across the entire critical path, time extension requests will be extremely hard to justify by the contractor, especially when the delay is experienced early in the project (e.g. "Activity 33100 has 30 days of float; How can a weeks worth of delay to install of this one line impact the project completion milestone?").

To understand why the total float values for the automatically leveled activities are incorrect, we will again focus on the summary electrical and detailed mechanical activities in Area 3. In terms of physical logic, all 5 mechanical activities are assumed to be independent and can therefore be executed concurrently. The 40 day electrical activity is reflected as part of the critical path, since it currently controls the commencement of Start-up (Activity 40000). Even though the each of the above-ground pipe installation activities are also tied with physical logic to Start-up, none currently have total float values reflecting that they would also be critical if executed in sequence due to resource constraints (see Figure 9 below).

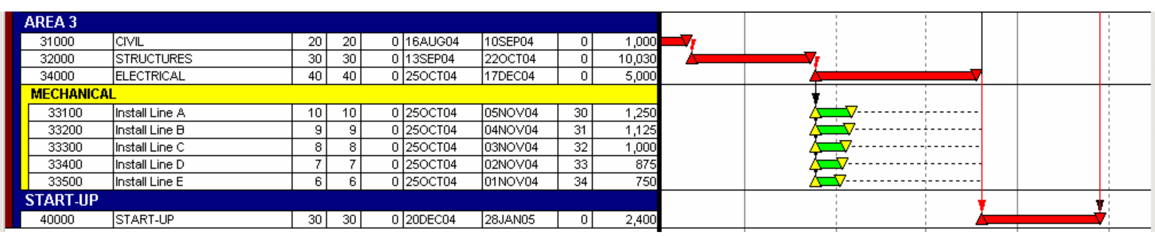

Figure 9: Area 3 mechanical activities before leveling.

Remember that the contractor's mechanical resource plan only allowed for one crew working a maximum of 150 labor-hours/day in Area 3, or 18 workers total. After automatically resource leveling for this upper limit of labor hours (and specifying the heuristics we discussed previously), the activities are sequenced as if finish-to-start relationships were added (as shown below in Figure 10).

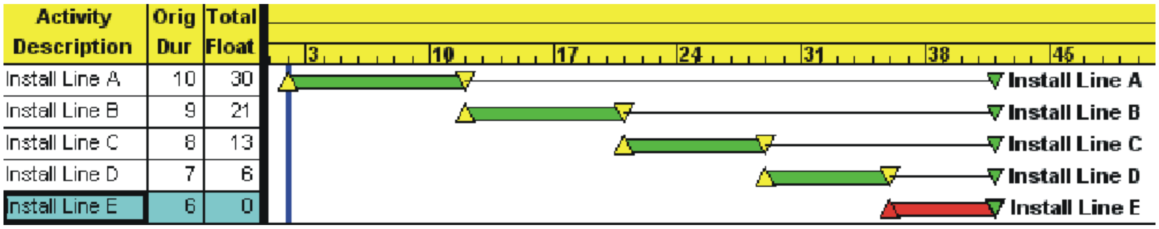

Figure 10: Area 3 Mechanical activities after automatic leveling.

In this screen shot, P3's single-line "float bars" have been utilized to underscore the issue. At first glance, the total float values for the mechanical activities have been decreased based on their new "leveled" sequence. Although the float has been adjusted (3), however, it is still incorrect since the late finish dates (the red, upside-down triangles in the float bars) for all mechanical activities are being calculated by the physical logic between them and start-up, not the interrelationship between the mechanical activities based on resource constraints. In other words, the scheduling software is not able to recognize the "resource ties" between the activities, and thereby cannot calculate a total float value for them that reflects the activity path as continuous.

Schedule Updates

The problem with total float values notwithstanding, the real strength of automatic leveling is displayed when we look at the same weekly update period in our sample schedule (Figure 11 below). As before, activity 33300 (Install Line C) is underway while installation of the other lines has not started. In this example, however, resource-constrained automatic leveling has been applied.

(3) Unlike P3, P3e/c does not adjust the activity's float after leveling. The float value remains constant from their pre-leveled settings.

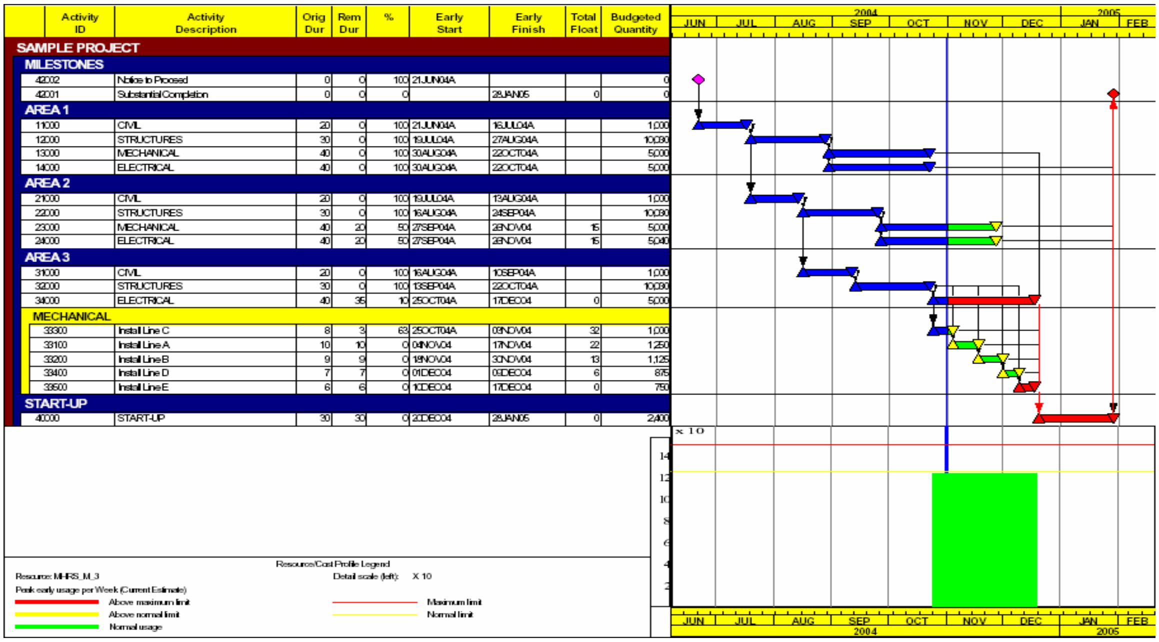

Figure 11: Weekly update with automatic leveling.

As you can see, the all-green histogram still shows the originally planned resource utilization (yellow line is normal limit of 125 labor-hours/day.) P3 then has re-sequenced the remaining lines that will be installed after Line C is complete, using the same general heuristics (early start, then total float). The overall duration of all five mechanical activities is still 40 work days, which because of their finish to start tie to Start-up should make the entire path critical along with the Area 3 electrical activity.

However, the float values of most of these activities are still greater than 0 (non-critical), and different for each. Not only is this inconsistent with the requirements of the contract specification we discussed earlier, it is also not reflective of reality since a delay to any of the Area 3 mechanical activities will delay Start-up as well as the project's overall completion.

Modeling the Real World

Resource leveling does not only involve labor-related resource constraints; very often the amount and types of construction equipment is a limiting factor on a project. This is especially true for sites with limited access, since a contractor does not have the option of forcing as much equipment as he may need into the same constricted area. A perfect example would involve the crane required to set and strip large concrete formwork that is required in most treatment plant construction projects such as our simplified example.

In our sample project, an 888 crane has been loaded as a resource into all concrete structures activities, and also selected to be automatically leveled. Since the site is only large enough to support 1 crane of this size due to access and swing radius clearance, the resource limit set in P3 is 1/day for both normal and maximum. The leveling heuristics used will be the same as before (early start, then float.) Figure 12 below shows the result of the resource leveling process.

	Activity ID	Activity Description	Orig Dur	Rem Dur	%	Early Start	Early Finish	Total Float	Budgeted Quantity
SAMPLE PROJECT									
MILESTONES									
	42002	Notice to Proceed	0	0	0	21JUN04		20	0
	42001	Substantial Completion	0	0	0		25FEB05	0	0
AREA 1									
	11000	CIVIL	20	20	0	21JUN04	16JUL04	20	1,000
	12000	STRUCTURES	30	30	0	19JUL04	27AUG04	60	10,030
	13000	MECHANICAL	40	40	0	30AUG04	22OCT04	60	5,000
	14000	ELECTRICAL	40	40	0	30AUG04	22OCT04	60	5,000
AREA 2									
	21000	CIVIL	20	20	0	19JUL04	13AUG04	20	1,000
	22000	STRUCTURES	30	30	0	30AUG04	08OCT04	30	10,030
	23000	MECHANICAL	40	40	0	11OCT04	03DEC04	30	5,000
	24000	ELECTRICAL	40	40	0	11OCT04	03DEC04	30	5,040
AREA 3									
	31000	CIVIL	20	20	0	16AUG04	10SEP04	20	1,000
	32000	STRUCTURES	30	30	0	11OCT04	19NOV04	0	10,030
	34000	ELECTRICAL	40	40	0	22NOV04	14JAN05	0	5,000
MECHANICAL									
	33100	Install Line A	10	10	0	22NOV04	03DEC04	30	1,250
	33200	Install Line B	9	9	0	06DEC04	16DEC04	21	1,125
	33300	Install Line C	8	8	0	17DEC04	28DEC04	13	1,000
	33400	Install Line D	7	7	0	29DEC04	06JAN05	6	875
	33500	Install Line E	6	6	0	07JAN05	14JAN05	0	750
START-UP									
	40000	START-UP	30	30	0	17JAN05	25FEB05	0	2,400

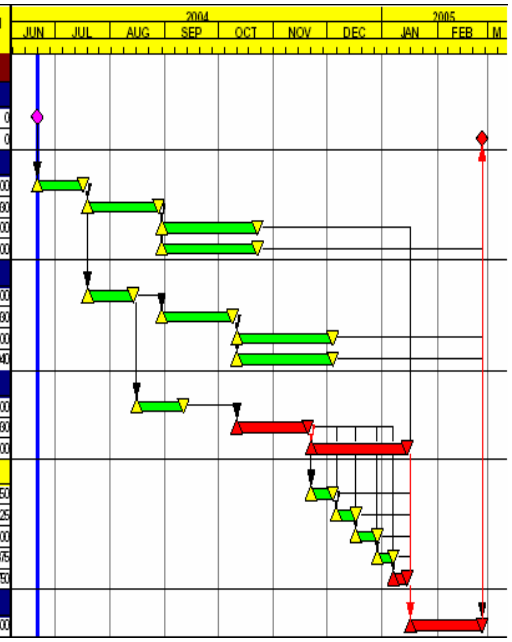

Figure 12: Revised baseline leveled for crane constraint.

Structures work in Area 3 has been delayed to allow for Area 2 to complete first. As a result, the overall project duration has been extended to 8 months, or a month longer than the schedule showed without leveling for the crane. While this overall duration is more realistic, the critical path is still discontinuous (structures in both Areas 1 and 2 should now also show as critical). In addition, the corresponding float values are even more inconsistent, which makes the use of this model hard to justify in relation to the specification requirement we have continued to discuss throughout this paper.

The contractor in our example now chooses to reflect additional resource constraints in their project schedule. The electrical subcontractor that will be used has qualified their bid such that each area can only support a single electrical crew/day. Figure 13 below shows that the electrical crew (Budgeted Quantity of 1/day) has been loaded into each electrical activity—this limit is also reflected in P3's resource limits (normal and maximum).

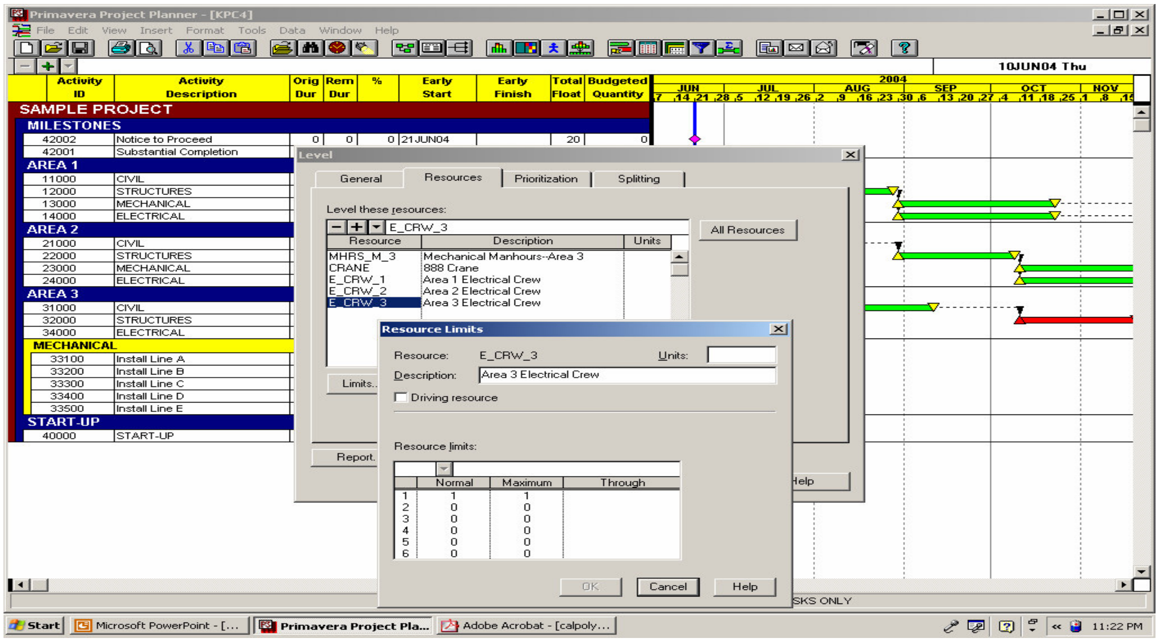

Figure 13: Additional leveling settings for electrical crew constraints.

The additional leveling applied to electrical activities does not change the schedule or resulting overall duration, since this summary schedule has only identified 1 electrical activity per area (the 1 crew/day limit will therefore not be exceeded). The late finish date of February 25, 2005 is now set as a "finish-no-later-than" constraint, since this is the best approximation of the project's overall duration with all resource constraints considered.

This final baseline will now be revised to reflect the receipt of an early electrical change order in Area 2. While this new electrical activity receives the same predecessors and successors as the base electrical in Area 2, no physical logic ties have been added between the two since the change is for additional electrical scope unrelated to base work. The contractor's schedule is now re-leveled using same limit of 1 electrical crew/day/area (Figure 14 below). Start-up is now delayed by Area 2 electrical, resulting in a slippage of 10 additional days from the late finish date of February 25, 2005.

Activity ID	Activity Description	Orig Dur	Rem Dur	%	Early Start	Early Finish	Total Float
SAMPLE PROJECT							
MILESTONES							
42002	Notice to Proceed	0	0	0	21JUN04		20
42001	Substantial Completion	0	0	0		11MAR05	-10
AREA 1							
11000	CIVIL	20	20	0	21JUN04	16JUL04	20
12000	STRUCTURES	30	30	0	19JUL04	27AUG04	60
13000	MECHANICAL	40	40	0	30AUG04	22OCT04	60
14000	ELECTRICAL	40	40	0	30AUG04	22OCT04	60
AREA 2							
21000	CIVIL	20	20	0	19JUL04	13AUG04	20
22000	STRUCTURES	30	30	0	30AUG04	08OCT04	30
23000	MECHANICAL	40	40	0	11OCT04	03DEC04	30
24000	ELECTRICAL	40	40	0	11OCT04	03DEC04	30
24001	Electrical Change Order 1	40	40	0	06DEC04	28JAN05	-10
AREA 3							
31000	CIVIL	20	20	0	16AUG04	10SEP04	20
32000	STRUCTURES	30	30	0	11OCT04	19NOV04	0
34000	ELECTRICAL	40	40	0	22NOV04	14JAN05	0
MECHANICAL							
33100	Install Line A	10	10	0	22NOV04	03DEC04	30
33200	Install Line B	9	9	0	06DEC04	16DEC04	21
33300	Install Line C	8	8	0	17DEC04	28DEC04	13
33400	Install Line D	7	7	0	29DEC04	06JAN05	6
33500	Install Line E	6	6	0	07JAN05	14JAN05	0
START-UP							
40000	START-UP	30	30	0	31JAN05	11MAR05	-10

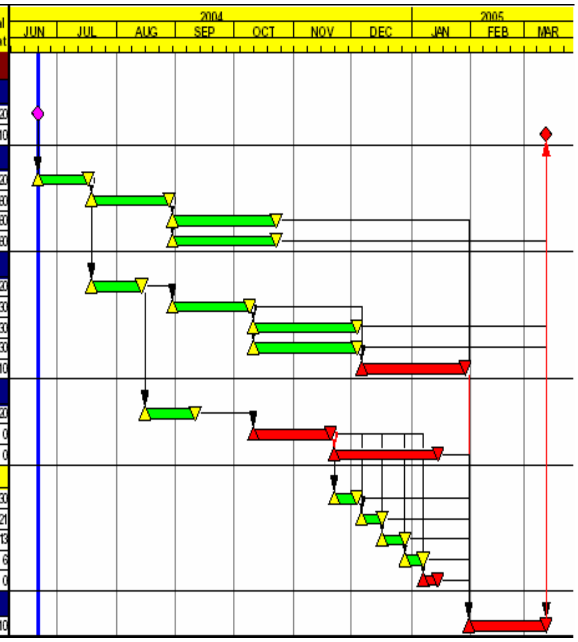

Figure 14: Impacted Baseline (electrical change order in Area 2).

Although a rather simplistic example was used in this case, this method has great potential for supporting cumulative impact claims where the impact of individual changes are not realized based on physical logic alone until they exceed a predetermined resource-related threshold. The problem remains, however, that the critical path is still discontinuous and total float values are inconsistent.

The solution to this problem is to combine the flexibility of automatic resource leveling with the "float accuracy" of preferential logic. In order to achieve this, an add-on software program is required to automatically generate the preferential logic ties necessary to re-create the resource-leveled schedule under normal CPM calculations. Once complete, the float values will correctly reflect the critical status of leveled activities, as well as providing for a contractually-defined method to show the impact of delay. Later, when a periodic update is due, the program must also automatically remove the preferential logic ties created earlier and perform the entire process again with a revised leveling plan that accounts for any changes from the original plan. Figure 15 shows just this sort of process using a software package that was developed by one of the authors as an add-on to P3, called *Logic League*. (4)

(4) Logic League is copyright 2003 by Ron Winter Consulting LLC.

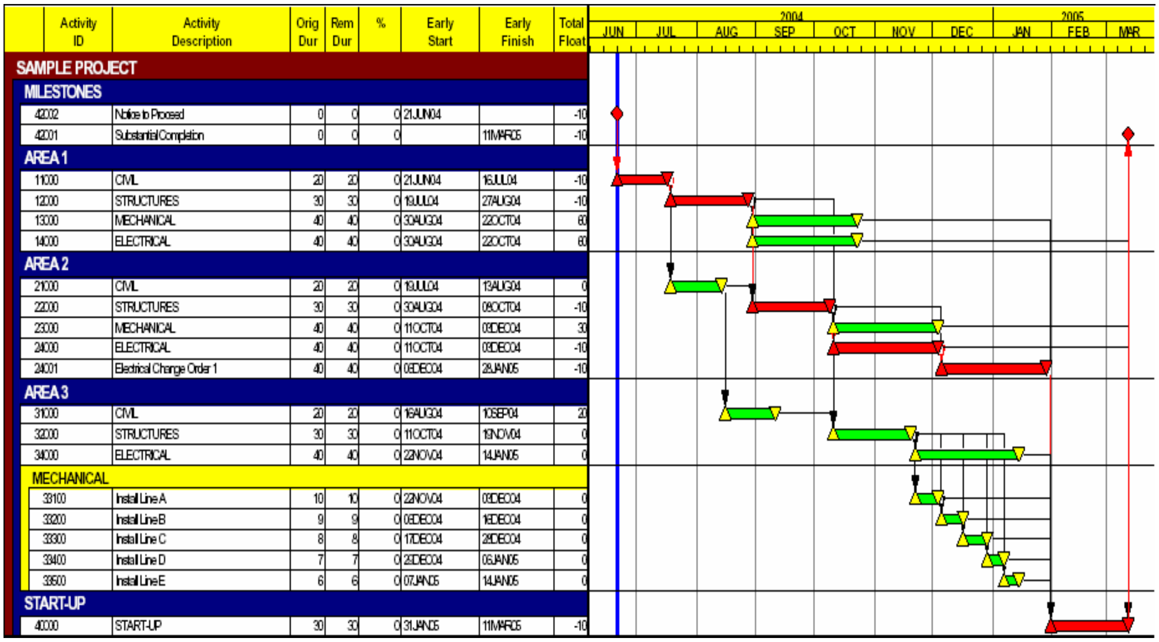

Figure 15: Revised baseline with "Logic League" applied.

The preferential relationship ties (called 'Resource Links' in Logic League) have been automatically applied to instances where activities have been delayed due to resource-constrained, automatic leveling. The critical path is now continuous throughout project, running through structures work in Areas 1 and 2, then the electrical activities in Area 2. Most importantly, total float values are consistent with the previously described expectations (-10 for the critical path.) As a result, this schedule is now in compliance with the contract specification discussed earlier.

Requirements

Before we go any further, it is important to discuss the requirements for implementing this process. For effective use of resource leveling/resource links on a project, the implementation must be both transparent and fair for all parties concerned. What is it going to take to implement this process fairly for the owner of a project? Education, documentation, and a commitment by the contractor to work the resource plan.

While this paper is a first step in the education process, most project owners don't really need to know how to perform resource leveling with P3 and Logic League. What they need to understand is that even though they are paying a contractor to complete a certain project for them, that contractor has a plan for making a profit on the project that revolves around an efficient use of resources. In addition, there needs to be a conscious effort on the part of the contractor in attempting to adhere to the original resource plan, as well as formally revising it when changes occur.

Documentation involves an explanation of this plan, and really exists at three levels. First, the individual activity resource requirements should be listed and validated. Only the 'controlling' resources need to be described in detail, and their requirements should be investigated for accuracy. Next, the actual resource availability limits need to be detailed. Consideration must be made for crowding in confined areas, bid design, and supervisory control. Finally, the heuristics and other resource leveling settings need to be documented. Since not all settings will always produce the best result, various leveling parameters should be evaluated for the best fit in a particular project situation.

The number of resource leveling parameters available to be optimized is staggering. Are the smoothing levels used correct and validated? Are the maximum availability limits used correct and validated? Is the maximum over-limit reasonable for this project? Has the number of times and for how long may activities be split been validated? Has what resources are being used for leveling been validated? Seeing that there is no one 'optimum' set of resource leveling rules, how may rules set combinations have been tried to determine that the one provided is the optimum one? There are 60! = 80 x 10^80 possible combinations of settings that could possibly be used. This paper does not intend to define the single best method to be used, since leveling parameters will always be project specific. As the use of resource leveling becomes more widespread in construction, however, recommended practices can be developed that will help standardize the practice.

CONCLUSION

Most project controls professionals understand that construction schedules that do not consider resource constraints are unrealistic. Accordingly, it appears to the authors that the practice of contractors electing to provide resource-loaded schedules is on the rise. Once a schedule has resources loaded into it, it is pretty clear that there are real advantages of using automatic resource leveling rather than manual leveling with preferential logic.

It seems to us then, that the use of resource-leveled schedules would also be on the rise if they could be made to conform to contract requirements regarding total float values. Software like Logic League has finally made this possible. Contractors can regain the flexibility to use the CPM schedule as a tool to manage their projects, while project owners will appreciate the transparency and objectiveness of using resource leveling over the manual insertion and deletion of preferential logic with every update.

Finally, as the practice of resource leveling becomes more common in the construction industry, project owners will expect guidelines to be codified by professional bodies such as the AACEi. AACEi can and should take the lead in establishing recommended practices and standards for resource leveling. If we do not, then some other professional association may decide that they will do so, without the interests of all the industry's stakeholders in mind. Any volunteers?