EXTRACTING THE RESOURCE-CONSTRAINED CRITICAL/LONGEST PATH FROM A LEVELED SCHEDULE

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1.0 INTRODUCTION

Effective and efficient management of time and other resources is a core competency for successful companies in project-focused industries like construction. While the Critical Path Method (CPM) has long been used effectively for project time management, its failure to incorporate limitations in resources is a continuing (and early-recognized) liability [1, p.i]. Over the years, three basic approaches to overcoming this liability have been practiced in North America.

1.1 Resource Limitations: (Theoretical) Traditional Approach

The theoretical/traditional approach is to ignore resources in the schedule but control them in the field. In this approach, the primary purpose of the schedule is to define the critical and near-critical paths based on technological requirements (a.k.a. "hard logic") alone. The corresponding management philosophy allows non-critical activities to slip (consuming float) while resources – and management attention – are prioritized to those activities that drive the completion of the project. The obvious problem is that project schedules that ignore real-world resource limits are inherently optimistic. In addition, the focus on critical and near-critical paths can lead to underdeveloped scope and schedule of those activities that are perceived to be non-critical. In practice, those slipping non-critical activities can eventually become critical and continue to slip - delaying the project - as the result of inadequate resources. Baseline project schedules that fail to account for resource limitations do not represent a true and achievable plan for the work, especially away from the critical path. This can lead to rejection of the schedule. Finally, because many activities are routinely required to slip within their available float, rigorous variance analysis is of dubious value and can be misleading.

Essentially all of the large-scale engineering and construction projects in the author's experience of 30+ years have been scheduled using at least a modicum of schedule logic that was not 100% driven by technological requirements – hence the "Theoretical" prefix above.

1.2 Preferential Logic approach:

This approach introduces explicit activity sequencing constraints into the schedule logic that are based on resource limitations (a.k.a. "soft logic" or "preferential logic") rather than technological requirements. Typically, but not always, "resource loading" of schedule activities is performed, such that the time-variable demands for various resources can be checked against the expected limits. Preferential logic can be imposed to govern logical workflows among constrained resources, leading to a baseline project schedule that may be acceptable as representing an achievable plan. As long as such logic is at a high enough level (e.g. "First we'll construct Bldg A, then B, then C"), there are few complications. Preferential logic at more detailed levels of the schedule, however, can conflict with on-site decisions that are ultimately more valid (e.g. "Skipped piles 1A through 2F because of muddy conditions; moved on to 3A.") It is practically inevitable that some activities are allowed to proceed in conflict with their established logical predecessor relationships. Reconciling this out-of-sequence progress with the actual facts in the field – and correcting the logical ties to future activities – is necessary to maintain an accurate schedule forecast. This can be harder to do as the amount of preferential logic increases. The schedule's credibility as a management tool suffers.

While some preferential logic may reflect non-resource related aspects of the contractor's means and methods, the distinction seems rarely if ever clear in the schedule submittal. A baseline schedule narrative complying with RP 38R-06 – Documenting the Schedule Basis – may describe the overall methodology for using resource-driven and other preferential logic, but such documentation typically does not include an itemized list addressing each relationship in the schedule network. Furthermore, while such documentation may exist for the Baseline schedule, updating it to reflect out-of-sequence progress at each schedule update is labor intensive and is not typically performed.

1.3 Resource-Leveling approach:

Sometimes defined as "Resource Constrained Scheduling," this approach includes various analytical and heuristic (rule-based) methods to schedule work subject to both logical and resource constraints [2, p. 507]. In practice, resource leveling involves automatically delaying certain work (compared to the CPM-based schedule) pending the completion of other, more urgent work that demands the same resources. Unlike the preferential logic approach, resource leveling allows resource-constrained activities to be scheduled at achievable times – and at a high level of detail – while also adapting to out-of-sequence progress without extensive re-working of the schedule logic at each update. This can lead to higher confidence in the progressed schedule forecast. Unfortunately, Total Float and the associated Critical Path become unreliable after leveling [2, p. 507]. Consequently, the resource-leveling approach has not been widely adopted in construction and other industries where understanding of these metrics is regularly exposed to claims and litigation.

This paper is one result of the author's ongoing efforts to automatically trace driving and non-driving logic in complex Microsoft Project[1] (MSP)[2]schedules, including those where resource leveling has been applied. In particular, a practical method for inferring soft logic links from detailed resource leveling data is presented. Where necessary, intellectual rigor has been bypassed in favor of practical and repeatable results. While most of the discussion is illustrated using MSP examples, there are no obvious roadblocks to similar developments in Oracle Primavera P6[3] (P6)[4]. (In the context of the MSP examples, MSP-consistent terms – e.g. "tasks" and "slack" – are used.) Construction-oriented readers seeking a general comparison of MSP and P6 scheduling methodologies should refer to the introductory paper by F. Burak Evrenosoglu, PE CCE PSP and Ron Winter PSP [3, p.1].

[1] Microsoft® is either a registered trademark or a trademark of Microsoft Corporation in the United States and/or other countries.
[2] Unless noted otherwise, MSP Professional 2010 has been used for analysis and illustration of examples.
[3] Oracle® and Primavera® are registered trademarks of Oracle Corporation and/or its affiliates. Other names may be trademarks of their respective owners.
[4] Unless noted otherwise, P6 Professional R15.2 (x64) has been used for analysis and illustration of examples.

This paper is not intended to evaluate, critique, or make recommendations regarding the application of resource leveling in MSP or P6. Its primary purpose remains extraction and presentation of the implied schedule logic – including the critical path – after leveling is performed.

2.0 RESOURCE LEVELING BACKGROUND

The two dominant CPM-based scheduling tools in North America – P6 and MSP – provide options for heuristic leveling based on rule sets and algorithms that are distinct to the two tools. Both tools continue to display total float and critical path after leveling despite their dubious value. One web-based Microsoft trainer/blogger has enthusiastically proclaimed, "*The main goal* [of resource leveling] *is to have a* <u>*critical path that is corrected for resource dependencies*</u>." [4, p.1] Based on review of internet discussion boards and other websites, regular reliance on resource leveling seems to be much more common among MSP (as opposed to P6) users.

1.1 Resource Loading

The resource leveling process in MSP and P6 begins with specification of the resources to be used – including the anticipated availability limit of each resource – followed by "loading" of the resources to the project schedule. In MSP, individual resources are *assigned* to individual tasks reflecting a utilization that corresponds to the work and duration of the task. At the end of the process, an overall collection of time-scaled *assignments* links the project's resources and tasks. Figure 1 illustrates the relationships between Resources, Tasks, and Assignments in a simple example using MSP's "Resource Usage" view. The example depicts four resources distributed among four tasks, resulting in a total of nine assignments (shown in green).

Generally, each assignment possesses its own work and utilization properties, which aggregate to the associated resources and tasks. It inherits cost and calendar information from the associated resource while simultaneously inheriting CPM schedule information from the associated task. In MSP, the scheduler may impose a delay on starting the work assignment (compared to the start of the task) and may apply any one of eight *work contours* to control the time-scale distribution of the assignment's work (comparable to resource curves in P6). In addition, the scheduler may manually edit the time-scaled work distribution – down to the minute – if desired.

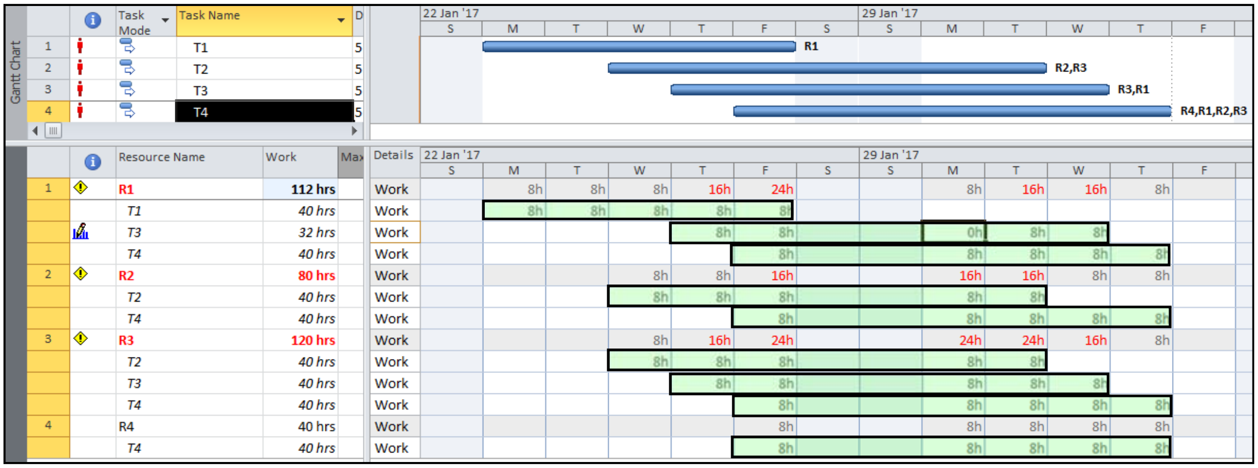


Figure 1: Tasks, Resources, and Assignments

1.2 Resource-Constrained Scheduling and Leveling Delay

After the resource assignments have been defined in MSP, resource leveling provides a scheduling mechanism for complying with *resource constraints* while simultaneously complying with logical precedence (i.e. CPM) constraints. It is synonymous with Resource-Constrained Scheduling. In practice, leveling involves selectively delaying the resource assignments (i.e. shifting the green bars in Figure 1 to the right) until all resource constraints have been satisfied or until other limits of the analysis have been reached. The decisions regarding which tasks, assignments, or assignment parts to delay are the result of MSP's proprietary rules and the following few leveling options:

- Run the leveler automatically (at each schedule recalculation) or manually (i.e. by clicking a specific leveling command).
- Adjust the time scale of the leveling interval, i.e. from minute-by-minute to month-by-month.
- Run the leveler only for specific resources or within a specific time window.
- Allow over-riding of MSP's proprietary urgency-ranking rules with a user specified task priority or with the task ID number.
- Level only within available slack – i.e. don't allow the leveler to extend the project or any constrained/deadlined tasks.
- Allow resources to start and finish work independently on the same task – thereby extending the task duration by allowing work to start before all required resources are available, though it cannot finish until the last resource assignment is complete.
- Allow assignments and their associated tasks to be interrupted (i.e. "split") so that resources may be diverted to more urgent tasks.

While MSP includes methods for dynamic adjustment of the task/resource/assignment relationships, such that a change in assigned work automatically adjusts the corresponding duration or resource utilization (i.e. "units"), such methods are actually part of the resource loading and are NOT resource leveling. In addition, where a single assignment demands resources that exceed the total availability of the resource, the resulting over-allocation cannot be resolved by leveling.

Explicit artifacts of the leveling process in MSP include the task leveling delay field and, if allowed, individual assignment leveling delay fields. Hidden artifacts of the leveling process can include task and assignment splits (i.e. dividing into parts) that are not otherwise explained.

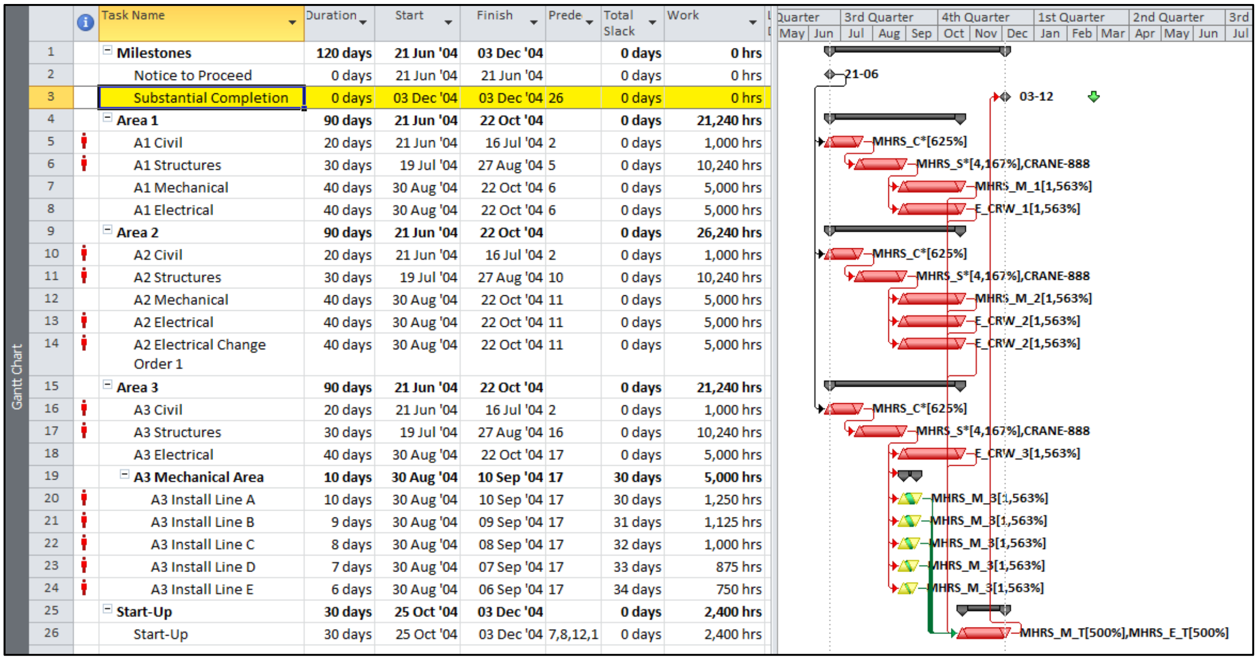
1.3 Phantom Float/Slack

Long recognized by researchers, the rule-based decisions to delay certain tasks in a resource-constrained scheduling process are not readily transformed to the CPM's model of early/late dates and total float. A major consequence of this conflict is the reporting of substantial total float for activities which are clearly on the resource-constrained critical path for the project. This excess float has been termed "phantom float" [2, p. 507] and is further explored in the following section.

3.0 PHANTOM FLOAT AND THE MISSING CRITICAL PATH

In MSP, Total Float/Slack values and the associated "critical" flags do not accurately reflect the logical consequences of the resource leveling process. The result can be a "critical path" that reflects neither the CPM nor the leveled project schedule.

Figure 2 – re-created after the example of Mssrs. Nosbisch and Winter [5, p.6] – is a simplified CPM model of a construction project involving multiple trades working in multiple areas. The model includes realistic resource loading, but the logical links have been limited to "hard logic" only (i.e. physical constraints). In other words, there is no preferential logic included in the schedule to guide the resource deployments. The default 5dx8h weekly calendar is universally applied, and a deadline (equivalent to a late finish constraint in P6) has been imposed on the Substantial Completion milestone to reflect a contract completion requirement of 25Feb'04. The unleveled CPM schedule includes a forecast completion that is nearly 3 months ahead of the deadline, but resources are severely over-allocated – the schedule is unrealistic and needs to be leveled.

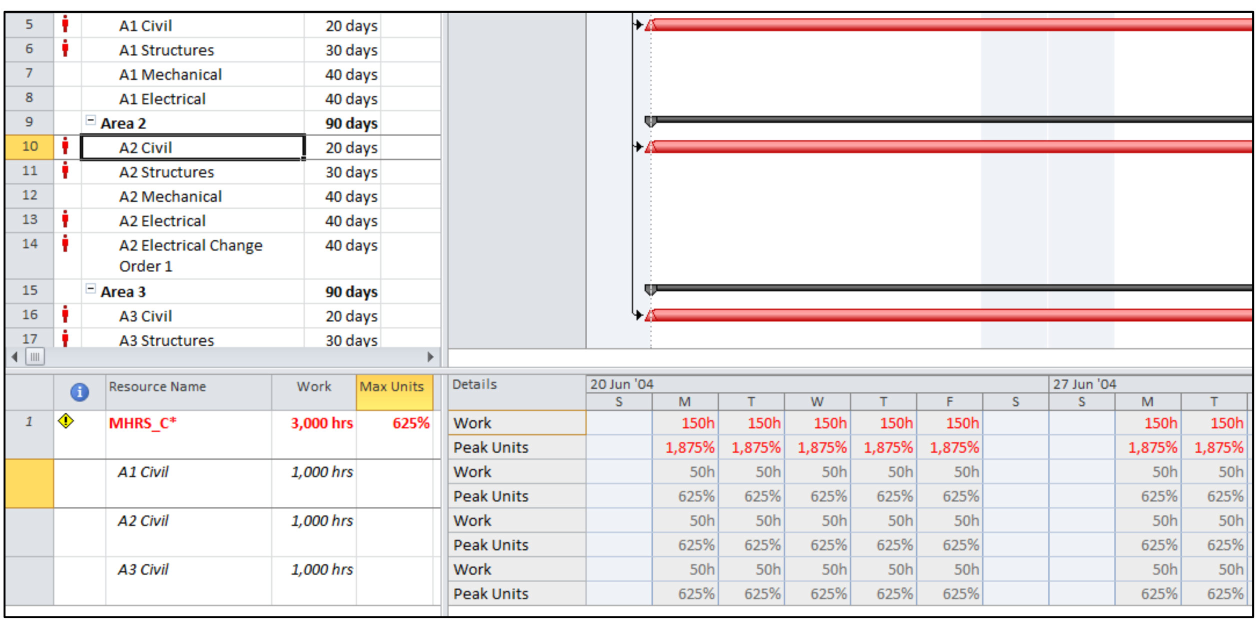


	Task Name	Duration	Start	Finish	Predecessors	Total Slack	Work
1	**Milestones**	**120 days**	**21 Jun '04**	**03 Dec '04**		**0 days**	**0 hrs**
2	Notice to Proceed	0 days	21 Jun '04	21 Jun '04		0 days	0 hrs
3	Substantial Completion	0 days	03 Dec '04	03 Dec '04	26	0 days	0 hrs
4	**Area 1**	**90 days**	**21 Jun '04**	**22 Oct '04**		**0 days**	**21,240 hrs**
5	A1 Civil	20 days	21 Jun '04	16 Jul '04	2	0 days	1,000 hrs
6	A1 Structures	30 days	19 Jul '04	27 Aug '04	5	0 days	10,240 hrs
7	A1 Mechanical	40 days	30 Aug '04	22 Oct '04	6	0 days	5,000 hrs
8	A1 Electrical	40 days	30 Aug '04	22 Oct '04	6	0 days	5,000 hrs
9	**Area 2**	**90 days**	**21 Jun '04**	**22 Oct '04**		**0 days**	**26,240 hrs**
10	A2 Civil	20 days	21 Jun '04	16 Jul '04	2	0 days	1,000 hrs
11	A2 Structures	30 days	19 Jul '04	27 Aug '04	10	0 days	10,240 hrs
12	A2 Mechanical	40 days	30 Aug '04	22 Oct '04	11	0 days	5,000 hrs
13	A2 Electrical	40 days	30 Aug '04	22 Oct '04	11	0 days	5,000 hrs
14	A2 Electrical Change Order 1	40 days	30 Aug '04	22 Oct '04	11	0 days	5,000 hrs
15	**Area 3**	**90 days**	**21 Jun '04**	**22 Oct '04**		**0 days**	**21,240 hrs**
16	A3 Civil	20 days	21 Jun '04	16 Jul '04	2	0 days	1,000 hrs
17	A3 Structures	30 days	19 Jul '04	27 Aug '04	16	0 days	10,240 hrs
18	A3 Electrical	40 days	30 Aug '04	22 Oct '04	17	0 days	5,000 hrs
19	**A3 Mechanical Area**	**10 days**	**30 Aug '04**	**10 Sep '04**	**17**	**30 days**	**5,000 hrs**
20	A3 Install Line A	10 days	30 Aug '04	10 Sep '04	17	30 days	1,250 hrs
21	A3 Install Line B	9 days	30 Aug '04	09 Sep '04	17	31 days	1,125 hrs
22	A3 Install Line C	8 days	30 Aug '04	08 Sep '04	17	32 days	1,000 hrs
23	A3 Install Line D	7 days	30 Aug '04	07 Sep '04	17	33 days	875 hrs
24	A3 Install Line E	6 days	30 Aug '04	06 Sep '04	17	34 days	750 hrs
25	**Start-Up**	**30 days**	**25 Oct '04**	**03 Dec '04**		**0 days**	**2,400 hrs**
26	Start-Up	30 days	25 Oct '04	03 Dec '04	7,8,12,1	0 days	2,400 hrs

Figure 2: Simple Construction Project with Resource Loading

Specifically:

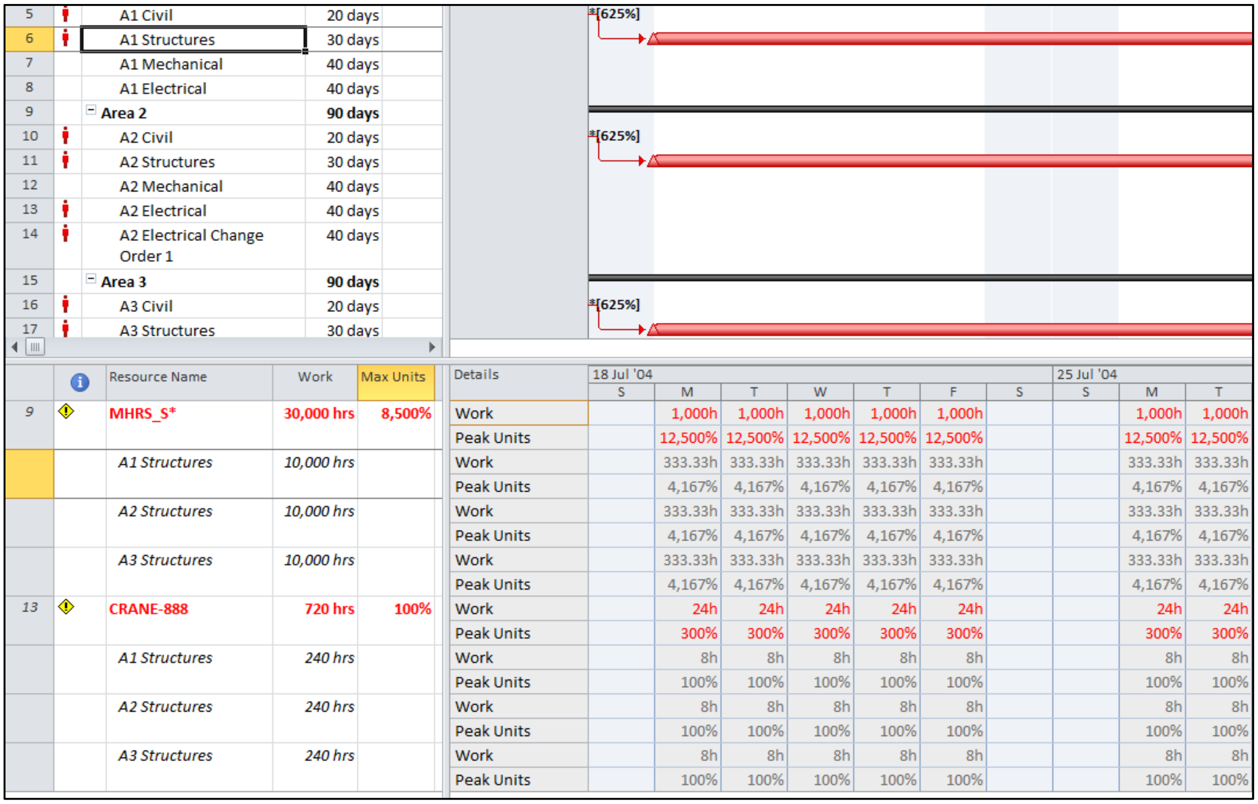
1. Three civil works tasks are running concurrently, but there is only sufficient manpower to run them sequentially. (Figure 3.)
2. Three structural tasks are also running concurrently, requiring manpower and a crane (Figure 4). They must be done sequentially.
3. There is room to install the five separate manufacturing lines concurrently, but there is only enough skilled manpower to install them sequentially. (Figure 5).
4. An electrical change order has been approved in area 2, but this requires the same specialized crew that is already working there. The Change-order work must be delayed (Figure 6).



	Task Name	Duration
5	A1 Civil	20 days
6	A1 Structures	30 days
7	A1 Mechanical	40 days
8	A1 Electrical	40 days
9	**Area 2**	**90 days**
10	A2 Civil	20 days
11	A2 Structures	30 days
12	A2 Mechanical	40 days
13	A2 Electrical	40 days
14	A2 Electrical Change Order 1	40 days
15	**Area 3**	**90 days**
16	A3 Civil	20 days
17	A3 Structures	30 days

	Resource Name	Work	Max Units	Details	20 Jun '04 S	M	T	W	T	F	S	27 Jun '04 S	M	T
1	MHRS_C*	3,000 hrs	625%	Work		150h	150h	150h	150h	150h			150h	150h
				Peak Units		1,875%	1,875%	1,875%	1,875%	1,875%			1,875%	1,875%
	A1 Civil	*1,000 hrs*		Work		50h	50h	50h	50h	50h			50h	50h
				Peak Units		625%	625%	625%	625%	625%			625%	625%
	A2 Civil	*1,000 hrs*		Work		50h	50h	50h	50h	50h			50h	50h
				Peak Units		625%	625%	625%	625%	625%			625%	625%
	A3 Civil	*1,000 hrs*		Work		50h	50h	50h	50h	50h			50h	50h
				Peak Units		625%	625%	625%	625%	625%			625%	625%

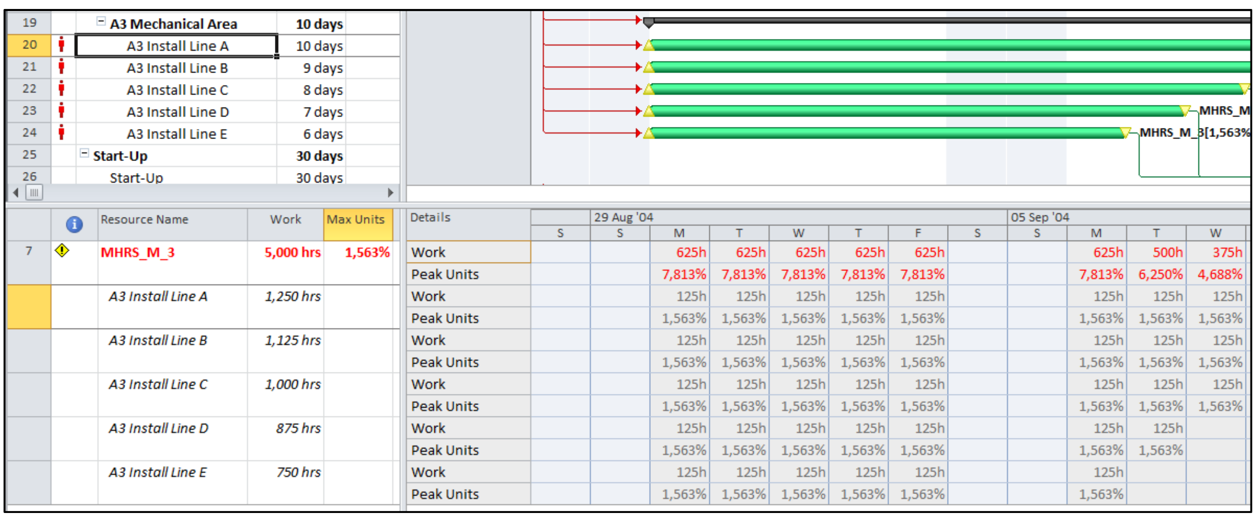
Figure 3: Over-Allocation of Civil Works Manpower



ID	Task Name	Duration
5	A1 Civil	20 days
6	A1 Structures	30 days
7	A1 Mechanical	40 days
8	A1 Electrical	40 days
9	Area 2	90 days
10	A2 Civil	20 days
11	A2 Structures	30 days
12	A2 Mechanical	40 days
13	A2 Electrical	40 days
14	A2 Electrical Change Order 1	40 days
15	Area 3	90 days
16	A3 Civil	20 days
17	A3 Structures	30 days

	Resource Name	Work	Max Units	Details	18 Jul '04 S	M	T	W	T	F	S	25 Jul '04 S	M	T
9	MHRS_S*	30,000 hrs	8,500%	Work		1,000h	1,000h	1,000h	1,000h	1,000h			1,000h	1,000h
				Peak Units		12,500%	12,500%	12,500%	12,500%	12,500%			12,500%	12,500%
	A1 Structures	10,000 hrs		Work		333.33h	333.33h	333.33h	333.33h	333.33h			333.33h	333.33h
				Peak Units		4,167%	4,167%	4,167%	4,167%	4,167%			4,167%	4,167%
	A2 Structures	10,000 hrs		Work		333.33h	333.33h	333.33h	333.33h	333.33h			333.33h	333.33h
				Peak Units		4,167%	4,167%	4,167%	4,167%	4,167%			4,167%	4,167%
	A3 Structures	10,000 hrs		Work		333.33h	333.33h	333.33h	333.33h	333.33h			333.33h	333.33h
				Peak Units		4,167%	4,167%	4,167%	4,167%	4,167%			4,167%	4,167%
13	CRANE-888	720 hrs	100%	Work		24h	24h	24h	24h	24h			24h	24h
				Peak Units		300%	300%	300%	300%	300%			300%	300%
	A1 Structures	240 hrs		Work		8h	8h	8h	8h	8h			8h	8h
				Peak Units		100%	100%	100%	100%	100%			100%	100%
	A2 Structures	240 hrs		Work		8h	8h	8h	8h	8h			8h	8h
				Peak Units		100%	100%	100%	100%	100%			100%	100%
	A3 Structures	240 hrs		Work		8h	8h	8h	8h	8h			8h	8h
				Peak Units		100%	100%	100%	100%	100%			100%	100%

Figure 4: Over-Allocation of Structural Erection Manpower and Crane



ID	Task Name	Duration
19	A3 Mechanical Area	10 days
20	A3 Install Line A	10 days
21	A3 Install Line B	9 days
22	A3 Install Line C	8 days
23	A3 Install Line D	7 days
24	A3 Install Line E	6 days
25	Start-Up	30 days
26	Start-Up	30 days

	Resource Name	Work	Max Units	Details	S	29 Aug '04 S	M	T	W	T	F	S	05 Sep '04 S	M	T	W
7	MHRS_M_3	5,000 hrs	1,563%	Work			625h	625h	625h	625h	625h			625h	500h	375h
				Peak Units			7,813%	7,813%	7,813%	7,813%	7,813%			7,813%	6,250%	4,688%
	A3 Install Line A	1,250 hrs		Work			125h	125h	125h	125h	125h			125h	125h	125h
				Peak Units			1,563%	1,563%	1,563%	1,563%	1,563%			1,563%	1,563%	1,563%
	A3 Install Line B	1,125 hrs		Work			125h	125h	125h	125h	125h			125h	125h	125h
				Peak Units			1,563%	1,563%	1,563%	1,563%	1,563%			1,563%	1,563%	1,563%
	A3 Install Line C	1,000 hrs		Work			125h	125h	125h	125h	125h			125h	125h	125h
				Peak Units			1,563%	1,563%	1,563%	1,563%	1,563%			1,563%	1,563%	1,563%
	A3 Install Line D	875 hrs		Work			125h	125h	125h	125h	125h			125h	125h	
				Peak Units			1,563%	1,563%	1,563%	1,563%	1,563%			1,563%	1,563%	
	A3 Install Line E	750 hrs		Work			125h	125h	125h	125h	125h			125h		
				Peak Units			1,563%	1,563%	1,563%	1,563%	1,563%			1,563%		

Figure 5: Over-Allocation of Area 3 Specialized Mechanical Installation Manpower

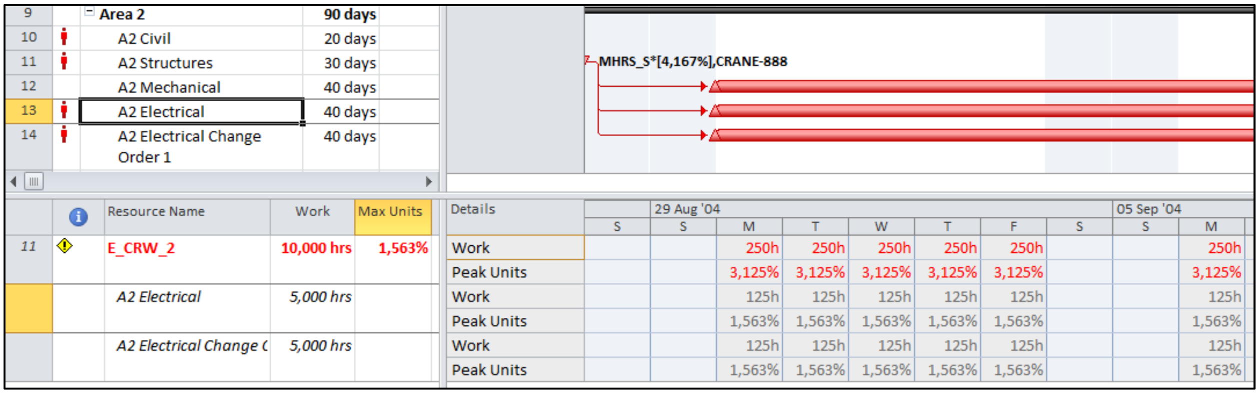


Figure 6: Over-Allocation of Area 2 Specialized Electrical Manpower

For this simple project, it is possible to remove the over-allocations by manually executing MSP's leveling engine using near-default conditions (Figure 7).

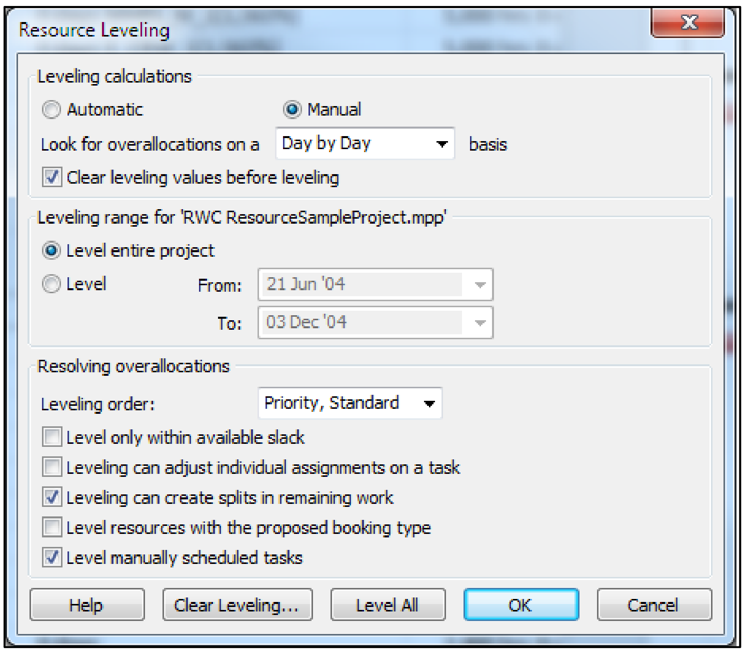
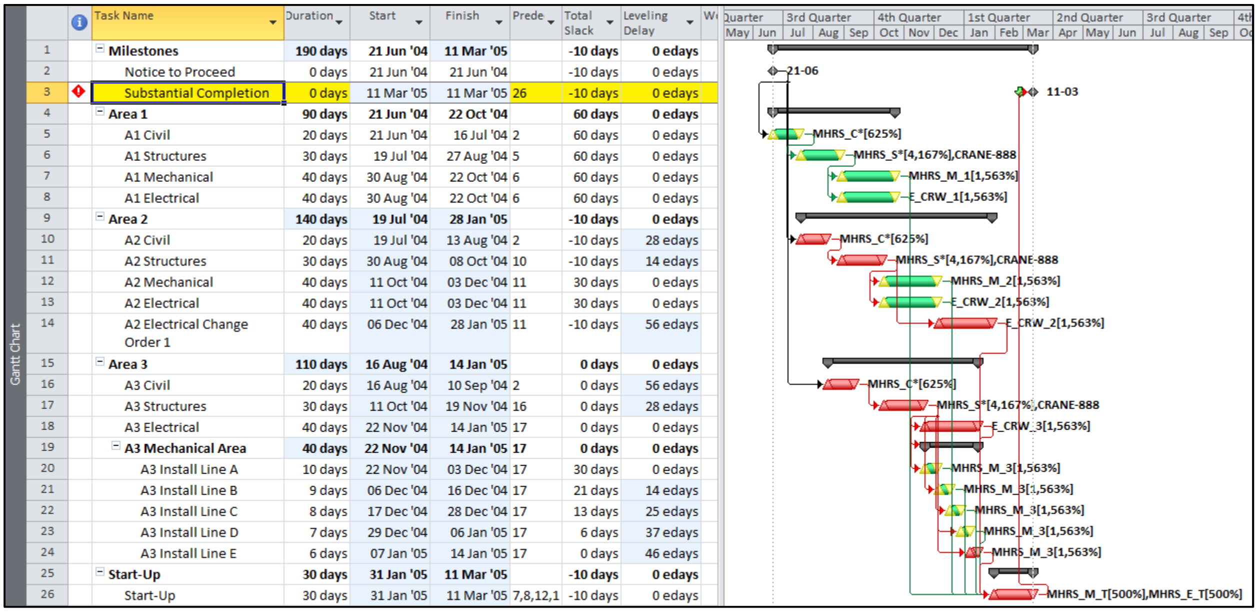


Figure 7: MSP Resource Leveling Options

The leveling engine resolves the over-allocations by selectively delaying those tasks (and task resource assignments, if specified) which are judged to be less urgent according to MSP's proprietary rules. Figure 8 illustrates the results of the leveling exercise:



	Task Name	Duration	Start	Finish	Prede	Total Slack	Leveling Delay
1	**Milestones**	**190 days**	**21 Jun '04**	**11 Mar '05**		**-10 days**	**0 edays**
2	Notice to Proceed	0 days	21 Jun '04	21 Jun '04		-10 days	0 edays
3	Substantial Completion	0 days	11 Mar '05	11 Mar '05	26	-10 days	0 edays
4	**Area 1**	**90 days**	**21 Jun '04**	**22 Oct '04**		**60 days**	**0 edays**
5	A1 Civil	20 days	21 Jun '04	16 Jul '04	2	60 days	0 edays
6	A1 Structures	30 days	19 Jul '04	27 Aug '04	5	60 days	0 edays
7	A1 Mechanical	40 days	30 Aug '04	22 Oct '04	6	60 days	0 edays
8	A1 Electrical	40 days	30 Aug '04	22 Oct '04	6	60 days	0 edays
9	**Area 2**	**140 days**	**19 Jul '04**	**28 Jan '05**		**-10 days**	**0 edays**
10	A2 Civil	20 days	19 Jul '04	13 Aug '04	2	-10 days	28 edays
11	A2 Structures	30 days	30 Aug '04	08 Oct '04	10	-10 days	14 edays
12	A2 Mechanical	40 days	11 Oct '04	03 Dec '04	11	30 days	0 edays
13	A2 Electrical	40 days	11 Oct '04	03 Dec '04	11	30 days	0 edays
14	A2 Electrical Change Order 1	40 days	06 Dec '04	28 Jan '05	11	-10 days	56 edays
15	**Area 3**	**110 days**	**16 Aug '04**	**14 Jan '05**		**0 days**	**0 edays**
16	A3 Civil	20 days	16 Aug '04	10 Sep '04	2	0 days	56 edays
17	A3 Structures	30 days	11 Oct '04	19 Nov '04	16	0 days	28 edays
18	A3 Electrical	40 days	22 Nov '04	14 Jan '05	17	0 days	0 edays
19	**A3 Mechanical Area**	**40 days**	**22 Nov '04**	**14 Jan '05**	**17**	**0 days**	**0 edays**
20	A3 Install Line A	10 days	22 Nov '04	03 Dec '04	17	30 days	0 edays
21	A3 Install Line B	9 days	06 Dec '04	16 Dec '04	17	21 days	14 edays
22	A3 Install Line C	8 days	17 Dec '04	28 Dec '04	17	13 days	25 edays
23	A3 Install Line D	7 days	29 Dec '04	06 Jan '05	17	6 days	37 edays
24	A3 Install Line E	6 days	07 Jan '05	14 Jan '05	17	0 days	46 edays
25	**Start-Up**	**30 days**	**31 Jan '05**	**11 Mar '05**		**-10 days**	**0 edays**
26	Start-Up	30 days	31 Jan '05	11 Mar '05	7,8,12,1	-10 days	0 edays

Figure 8: Resource-Leveled Schedule

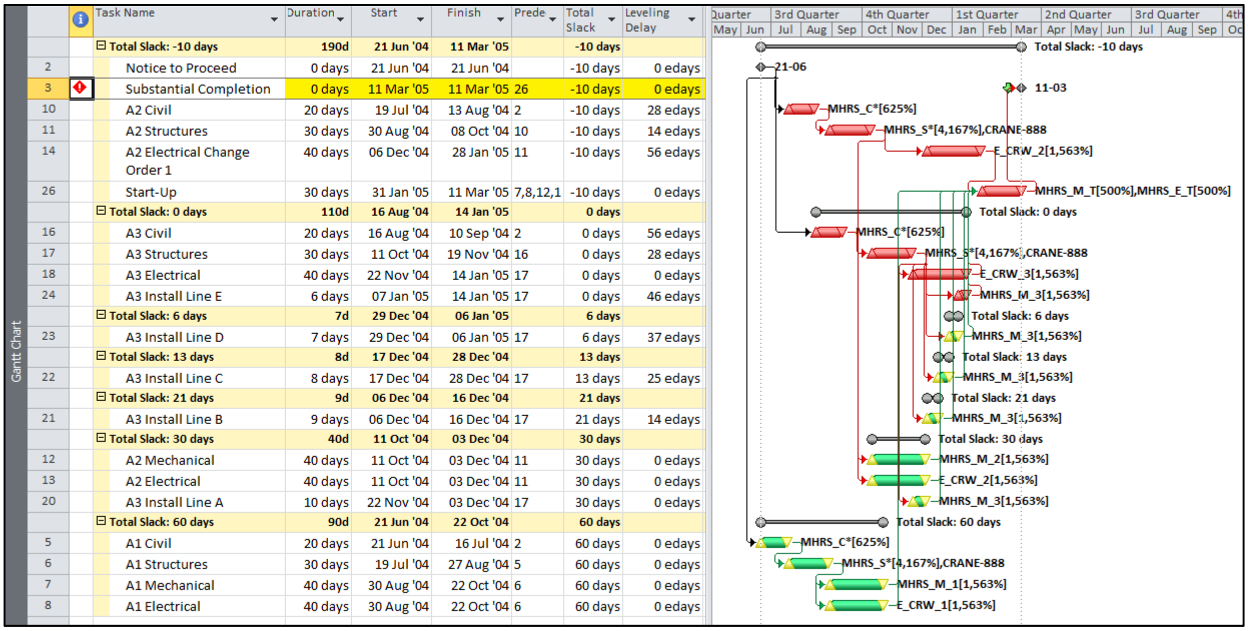
As indicated by the figure, MSP's resource leveler resolves the over-allocations by re-scheduling the lower-priority civil, structural, mechanical, and electrical tasks until resources become available. Substantial Completion is delayed until two weeks after the deadline, resulting in 10 days of negative slack on the milestone and its logical driving predecessors. There is not an obvious critical path (i.e. -10d total slack) from beginning to end of the project.

The primary artifact of the leveling process is the "leveling delay" task property, which is in units of elapsed-duration (i.e. "edays")[5]. The leveling delay is incorporated into the forward-pass schedule calculation, pushing the early start dates of the affected tasks. Leveling delay is also incorporated into the backward pass, accelerating the late dates and thereby removing "phantom slack" from logically-connected tasks.

Since the project includes neither multiple late constraints/deadlines nor variable calendars, the project's critical path (i.e. the longest path) *should be* effectively represented by the path with the lowest total slack. Figure 9 illustrates that the critical path by this measure (TS=-10d) is comprised of four tasks and two milestones separated by gaps, and the intervals of the gaps are determined by the "leveling delay." This does not describe a "resource constrained critical path." In fact, the obviously critical tasks without leveling delay – including the first (i.e. "A1") Civil and Structural tasks and the A2 Electrical task – now have high values of total slack (i.e. "phantom slack") and are shown far from the critical path.

It is clear therefore that Total Slack – which in the absence of a longest-path algorithm is MSP's only method for determining the critical path – is either useless or dangerously misleading in a leveled schedule.

[5] Elapsed duration units in MSP provide a shorthand mechanism for effectively applying a 7dx24h calendar to task durations and relationship lags. Its application to resource leveling delays is automatic and not user-selectable.



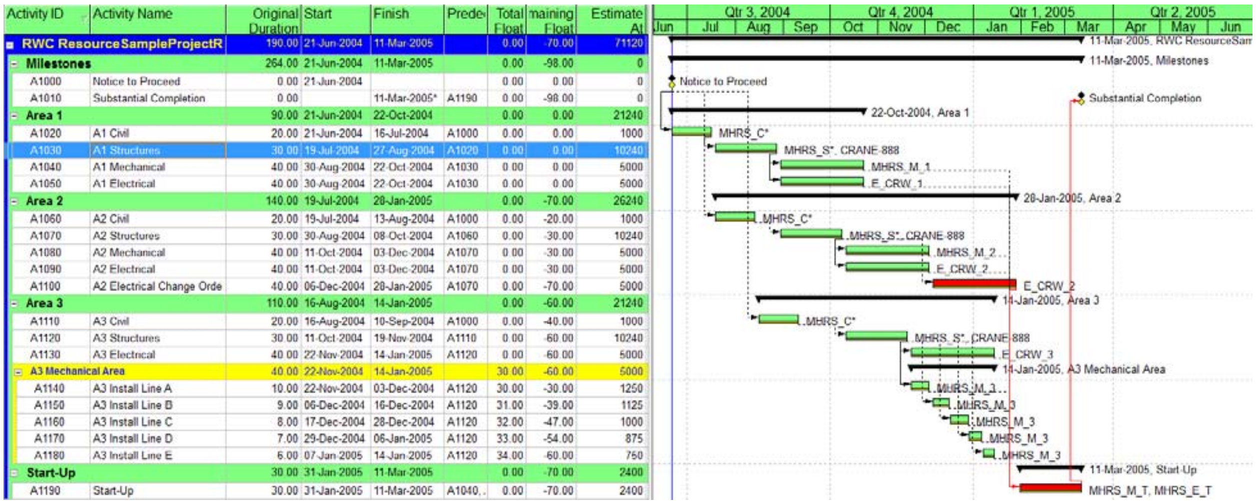
	Task Name	Duration	Start	Finish	Predecessors	Total Slack	Leveling Delay
	Total Slack: -10 days	190d	21 Jun '04	11 Mar '05		-10 days	
2	Notice to Proceed	0 days	21 Jun '04	21 Jun '04		-10 days	0 edays
3	Substantial Completion	0 days	11 Mar '05	11 Mar '05	26	-10 days	0 edays
10	A2 Civil	20 days	19 Jul '04	13 Aug '04	2	-10 days	28 edays
11	A2 Structures	30 days	30 Aug '04	08 Oct '04	10	-10 days	14 edays
14	A2 Electrical Change Order 1	40 days	06 Dec '04	28 Jan '05	11	-10 days	56 edays
26	Start-Up	30 days	31 Jan '05	11 Mar '05	7,8,12,1	-10 days	0 edays
	Total Slack: 0 days	110d	16 Aug '04	14 Jan '05		0 days	
16	A3 Civil	20 days	16 Aug '04	10 Sep '04	2	0 days	56 edays
17	A3 Structures	30 days	11 Oct '04	19 Nov '04	16	0 days	28 edays
18	A3 Electrical	40 days	22 Nov '04	14 Jan '05	17	0 days	0 edays
24	A3 Install Line E	6 days	07 Jan '05	14 Jan '05	17	0 days	46 edays
	Total Slack: 6 days	7d	29 Dec '04	06 Jan '05		6 days	
23	A3 Install Line D	7 days	29 Dec '04	06 Jan '05	17	6 days	37 edays
	Total Slack: 13 days	8d	17 Dec '04	28 Dec '04		13 days	
22	A3 Install Line C	8 days	17 Dec '04	28 Dec '04	17	13 days	25 edays
	Total Slack: 21 days	9d	06 Dec '04	16 Dec '04		21 days	
21	A3 Install Line B	9 days	06 Dec '04	16 Dec '04	17	21 days	14 edays
	Total Slack: 30 days	40d	11 Oct '04	03 Dec '04		30 days	
12	A2 Mechanical	40 days	11 Oct '04	03 Dec '04	11	30 days	0 edays
13	A2 Electrical	40 days	11 Oct '04	03 Dec '04	11	30 days	0 edays
20	A3 Install Line A	10 days	22 Nov '04	03 Dec '04	17	30 days	0 edays
	Total Slack: 60 days	90d	21 Jun '04	22 Oct '04		60 days	
5	A1 Civil	20 days	21 Jun '04	16 Jul '04	2	60 days	0 edays
6	A1 Structures	30 days	19 Jul '04	27 Aug '04	5	60 days	0 edays
7	A1 Mechanical	40 days	30 Aug '04	22 Oct '04	6	60 days	0 edays
8	A1 Electrical	40 days	30 Aug '04	22 Oct '04	6	60 days	0 edays

Figure 9: MSP Slack Paths of Leveled Schedule

Unlike MSP, P6 does not retain any "leveling delay" artifacts, and Float calculations after leveling appear somewhat contradictory. P6 reportedly keeps the CPM Total Float calculations unchanged after leveling, and the leveling impact is quantified by the Remaining (Total) Float property of each activity [6, p.13].

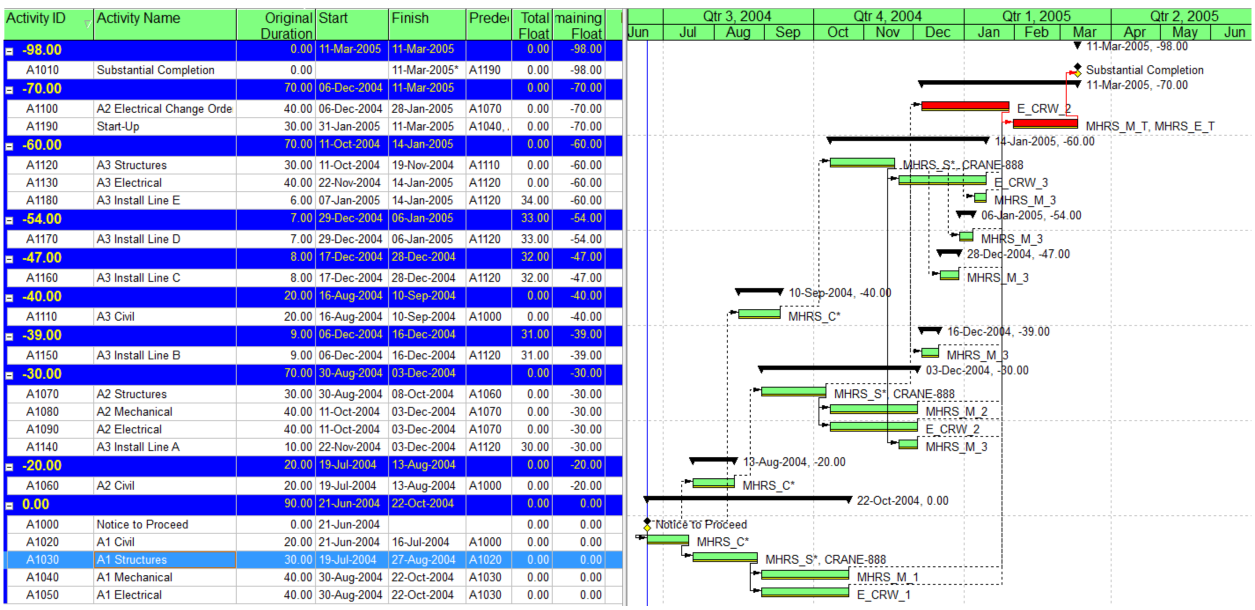
As shown in Figure 10, leveling with default options in P6[6] results in the same leveled schedule as MSP. The critical path (designated by the Longest Path option) is even more truncated than MSP's. Total Float is indeed frozen at the CPM-schedule values and is not useful. Finally, as shown in Figure 11, the Notice to Proceed has a Remaining Float of 0, and the Substantial Completion has a Remaining Float of -98 days. Both of these milestones are part of the known resource-constrained critical path for the project, but the Remaining Float does not indicate a correlation between them. Neither float value takes account of the late constraint on the Substantial Completion milestone. Thus, although perhaps not as dangerously misleading as MSP's Total Slack, neither Total Float nor Remaining Float appear useful for identifying the true critical path of a resource-constrained project schedule in P6.

[6] P6 Leveling Priorities ~ Activity Leveling Priority only (all activities equally ranked medium priority).



Activity ID	Activity Name	Original Duration	Start	Finish	Prede	Total Float	maining Float	Estimate At
RWC ResourceSampleProjectR		190.00	21-Jun-2004	11-Mar-2005		0.00	-70.00	71120
Milestones		264.00	21-Jun-2004	11-Mar-2005		0.00	-98.00	0
A1000	Notice to Proceed	0.00	21-Jun-2004			0.00	0.00	0
A1010	Substantial Completion	0.00		11-Mar-2005*	A1190	0.00	-98.00	0
Area 1		90.00	21-Jun-2004	22-Oct-2004		0.00	0.00	21240
A1020	A1 Civil	20.00	21-Jun-2004	16-Jul-2004	A1000	0.00	0.00	1000
A1030	A1 Structures	30.00	19-Jul-2004	27-Aug-2004	A1020	0.00	0.00	10240
A1040	A1 Mechanical	40.00	30-Aug-2004	22-Oct-2004	A1030	0.00	0.00	5000
A1050	A1 Electrical	40.00	30-Aug-2004	22-Oct-2004	A1030	0.00	0.00	5000
Area 2		140.00	19-Jul-2004	28-Jan-2005		0.00	-70.00	26240
A1060	A2 Civil	20.00	19-Jul-2004	13-Aug-2004	A1000	0.00	-20.00	1000
A1070	A2 Structures	30.00	30-Aug-2004	08-Oct-2004	A1060	0.00	-30.00	10240
A1080	A2 Mechanical	40.00	11-Oct-2004	03-Dec-2004	A1070	0.00	-30.00	5000
A1090	A2 Electrical	40.00	11-Oct-2004	03-Dec-2004	A1070	0.00	-30.00	5000
A1100	A2 Electrical Change Orde	40.00	06-Dec-2004	28-Jan-2005	A1070	0.00	-70.00	5000
Area 3		110.00	16-Aug-2004	14-Jan-2005		0.00	-60.00	21240
A1110	A3 Civil	20.00	16-Aug-2004	10-Sep-2004	A1000	0.00	-40.00	1000
A1120	A3 Structures	30.00	11-Oct-2004	19-Nov-2004	A1110	0.00	-60.00	10240
A1130	A3 Electrical	40.00	22-Nov-2004	14-Jan-2005	A1120	0.00	-60.00	5000
A3 Mechanical Area		40.00	22-Nov-2004	14-Jan-2005		30.00	-60.00	5000
A1140	A3 Install Line A	10.00	22-Nov-2004	03-Dec-2004	A1120	30.00	-30.00	1250
A1150	A3 Install Line B	9.00	06-Dec-2004	16-Dec-2004	A1120	31.00	-39.00	1125
A1160	A3 Install Line C	8.00	17-Dec-2004	28-Dec-2004	A1120	32.00	-47.00	1000
A1170	A3 Install Line D	7.00	29-Dec-2004	06-Jan-2005	A1120	33.00	-54.00	875
A1180	A3 Install Line E	6.00	07-Jan-2005	14-Jan-2005	A1120	34.00	-60.00	750
Start-Up		30.00	31-Jan-2005	11-Mar-2005		0.00	-70.00	2400
A1190	Start-Up	30.00	31-Jan-2005	11-Mar-2005	A1040,.	0.00	-70.00	2400

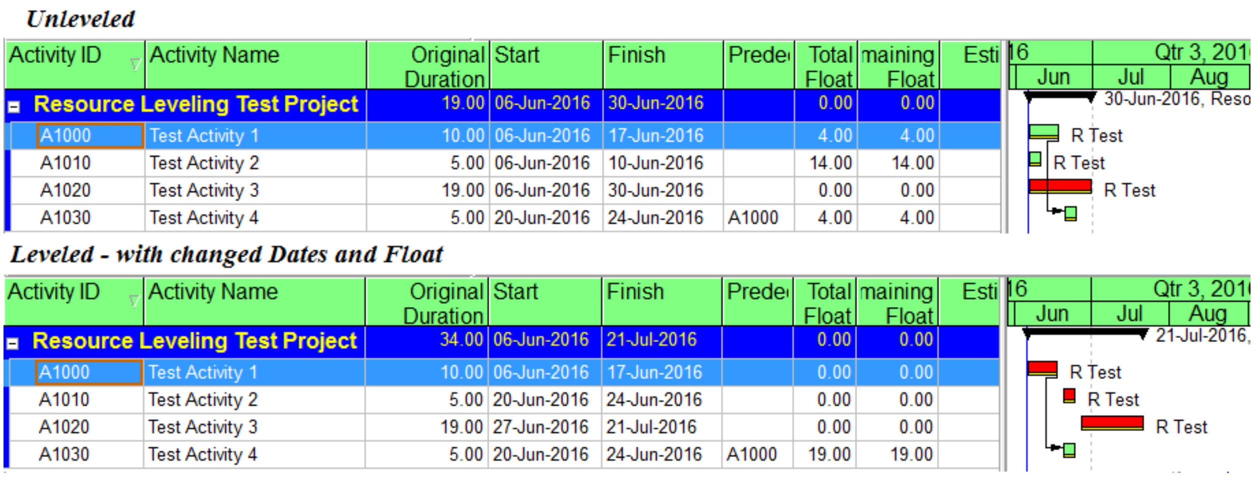
Figure 10: P6 Leveled Schedule



Activity ID	Activity Name	Original Duration	Start	Finish	Prede	Total Float	maining Float
-98.00		0.00	11-Mar-2005	11-Mar-2005		0.00	-98.00
A1010	Substantial Completion	0.00		11-Mar-2005*	A1190	0.00	-98.00
-70.00		70.00	06-Dec-2004	11-Mar-2005		0.00	-70.00
A1100	A2 Electrical Change Orde	40.00	06-Dec-2004	28-Jan-2005	A1070	0.00	-70.00
A1190	Start-Up	30.00	31-Jan-2005	11-Mar-2005	A1040,.	0.00	-70.00
-60.00		70.00	11-Oct-2004	14-Jan-2005		0.00	-60.00
A1120	A3 Structures	30.00	11-Oct-2004	19-Nov-2004	A1110	0.00	-60.00
A1130	A3 Electrical	40.00	22-Nov-2004	14-Jan-2005	A1120	0.00	-60.00
A1180	A3 Install Line E	6.00	07-Jan-2005	14-Jan-2005	A1120	34.00	-60.00
-54.00		7.00	29-Dec-2004	06-Jan-2005		33.00	-54.00
A1170	A3 Install Line D	7.00	29-Dec-2004	06-Jan-2005	A1120	33.00	-54.00
-47.00		8.00	17-Dec-2004	28-Dec-2004		32.00	-47.00
A1160	A3 Install Line C	8.00	17-Dec-2004	28-Dec-2004	A1120	32.00	-47.00
-40.00		20.00	16-Aug-2004	10-Sep-2004		0.00	-40.00
A1110	A3 Civil	20.00	16-Aug-2004	10-Sep-2004	A1000	0.00	-40.00
-39.00		9.00	06-Dec-2004	16-Dec-2004		31.00	-39.00
A1150	A3 Install Line B	9.00	06-Dec-2004	16-Dec-2004	A1120	31.00	-39.00
-30.00		70.00	30-Aug-2004	03-Dec-2004		0.00	-30.00
A1070	A2 Structures	30.00	30-Aug-2004	08-Oct-2004	A1060	0.00	-30.00
A1080	A2 Mechanical	40.00	11-Oct-2004	03-Dec-2004	A1070	0.00	-30.00
A1090	A2 Electrical	40.00	11-Oct-2004	03-Dec-2004	A1070	0.00	-30.00
A1140	A3 Install Line A	10.00	22-Nov-2004	03-Dec-2004	A1120	30.00	-30.00
-20.00		20.00	19-Jul-2004	13-Aug-2004		0.00	-20.00
A1060	A2 Civil	20.00	19-Jul-2004	13-Aug-2004	A1000	0.00	-20.00
0.00		90.00	21-Jun-2004	22-Oct-2004		0.00	0.00
A1000	Notice to Proceed	0.00	21-Jun-2004			0.00	0.00
A1020	A1 Civil	20.00	21-Jun-2004	16-Jul-2004	A1000	0.00	0.00
A1030	A1 Structures	30.00	19-Jul-2004	27-Aug-2004	A1020	0.00	0.00
A1040	A1 Mechanical	40.00	30-Aug-2004	22-Oct-2004	A1030	0.00	0.00
A1050	A1 Electrical	40.00	30-Aug-2004	22-Oct-2004	A1030	0.00	0.00

Figure 11: Remaining Float Paths of P6 Leveled Schedule

In contrast to the example project shown above, applying resource leveling to a simple P6 schedule with open ended logic can result in changed Total Float values that are consistent with the known resource-constrained critical path. See Figure 12. This behavior is not well understood and requires further study.



Unleveled

Activity ID	Activity Name	Original Duration	Start	Finish	Prede	Total Float	maining Float	Esti
Resource Leveling Test Project		19.00	06-Jun-2016	30-Jun-2016		0.00	0.00	
A1000	Test Activity 1	10.00	06-Jun-2016	17-Jun-2016		4.00	4.00	
A1010	Test Activity 2	5.00	06-Jun-2016	10-Jun-2016		14.00	14.00	
A1020	Test Activity 3	19.00	06-Jun-2016	30-Jun-2016		0.00	0.00	
A1030	Test Activity 4	5.00	20-Jun-2016	24-Jun-2016	A1000	4.00	4.00	

Leveled - with changed Dates and Float

Activity ID	Activity Name	Original Duration	Start	Finish	Prede	Total Float	maining Float	Esti
Resource Leveling Test Project		34.00	06-Jun-2016	21-Jul-2016		0.00	0.00	
A1000	Test Activity 1	10.00	06-Jun-2016	17-Jun-2016		0.00	0.00	
A1010	Test Activity 2	5.00	20-Jun-2016	24-Jun-2016		0.00	0.00	
A1020	Test Activity 3	19.00	27-Jun-2016	21-Jul-2016		0.00	0.00	
A1030	Test Activity 4	5.00	20-Jun-2016	24-Jun-2016	A1000	19.00	19.00	

Figure 12: Simple P6 Example Showing Float Change

4.0 IDENTIFYING RESOURCE DRIVERS

Numerous methods for alleviating the phantom float/slack problem in resource constrained schedules have been proposed since recognition of the problem in the 1960s. With the major software tools (P6 and MSP) having settled on optional application of heuristic leveling algorithms in the context of a CPM solution, more recent proposals to essentially create logical links from leveling decisions have been intriguing [7, p. 29]. The present work, in fact, was partly inspired by author Ron Winter's earlier proposals to manage logical links – including specifically categorized preferential logic links that could be inferred from resource leveling decisions – in an external database [8, p.1]. Such a database would facilitate automatic updating of such preferential logic using the leveling algorithm of the CPM software.

The goal of the present work is less ambitious – to extract and present, not manage, the consequences of the resource-driven pseudo-logic that is left behind by MSP's leveling process. Fortunately, the *leveling delay* artifacts provide a good starting point for defining these resource drivers.

Inspection of the leveled example project in Figure 8 indicates that the A2 Civil task has 28 elapsed days of leveling delay. It may be intuitively obvious to the scheduler that this delay results from the unavailability of the MHRS_C* resource pending completion of the A1 Civil task. More specifically, as shown in Figure 13:

1. A2 Civil has a leveling delay.
2. The first resource assignment for A2 Civil – MHRS_C* - starts on Monday 19Jul'04, when it gains access to the resource.
3. A scan of all other assignments demanding the same resource finds one assignment (A1 Civil – MHRS_C*) that:
    a. Uses the resource on the last workday before the start of the present assignment;
    b. No longer uses the resource at the start of the present assignment;
    c. (Therefore) appears to release the resource for use in the present assignment.
4. A Finish-to-Start "resource-driving" link between the two corresponding tasks is inferred.

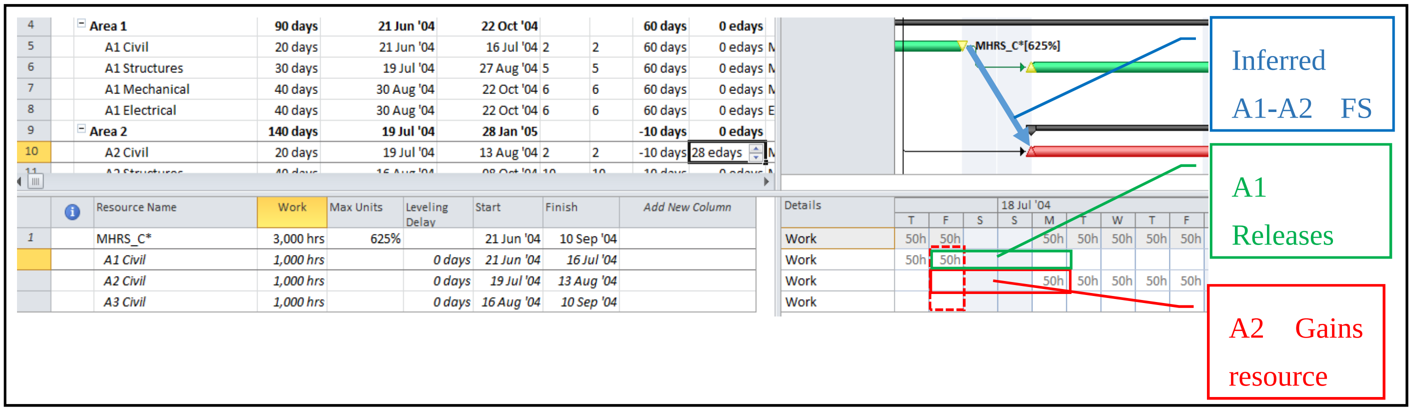


Figure 13: Inferred Resource Driver Link – A1 Civil to A2 Civil

Figure 14 illustrates a similar analysis of the leveling delay at the A2 Structures task, which has two resource assignments: MHRS_S* and CRANE-888. Competing demands for the two resources are evaluated independently, and the A1 Structures task is identified as releasing both resources simultaneously. Another resource-driving link is inferred.

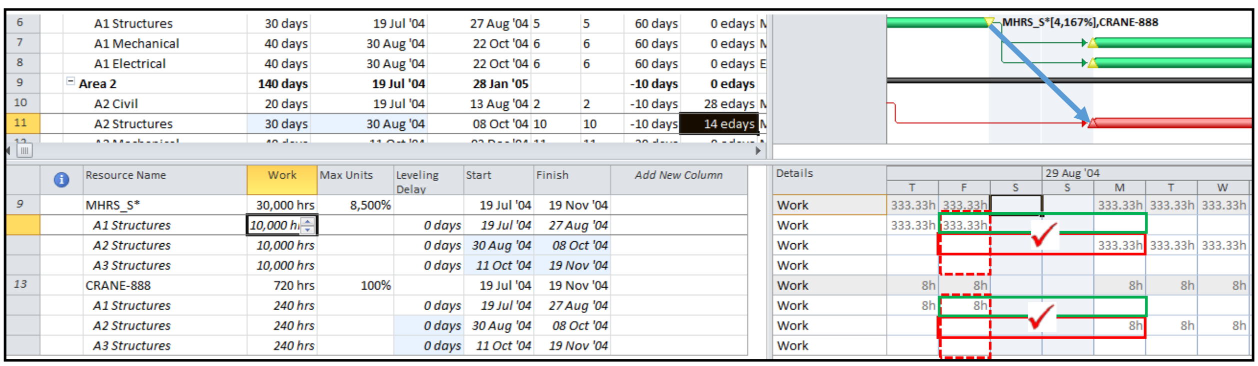


Figure 14: Inferred Resource Driver Link – A1 Structures to A2 Structures

In detailed application, the method must be applied at a time scale corresponding to the interval used in the leveling options. Further adjustments must be made to allow for calendar differences (if any) between the resource-releasing and resource-gaining tasks. Finally, if the leveling process has been allowed to split tasks and assignments, then the detailed analysis shown must be extended to include the start and finish of the various split parts.

The project was leveled with the "Leveling can adjust individual assignments on a task" option un-checked. As shown in Figure 15, checking this option instead would have allowed the A2 Structures task to start on-time (i.e. no task leveling delay) using labor but no crane and to finish 2 weeks late using a crane with no labor. This is clearly unworkable in this project! Nevertheless, in cases where independent leveling of resource assignments is justified, then a detailed analysis of the resource assignments as shown can readily infer a resource-driving link between the extended portion of the task and the previous task that is responsible for delaying the resource (even though the task itself has no leveling delay.)

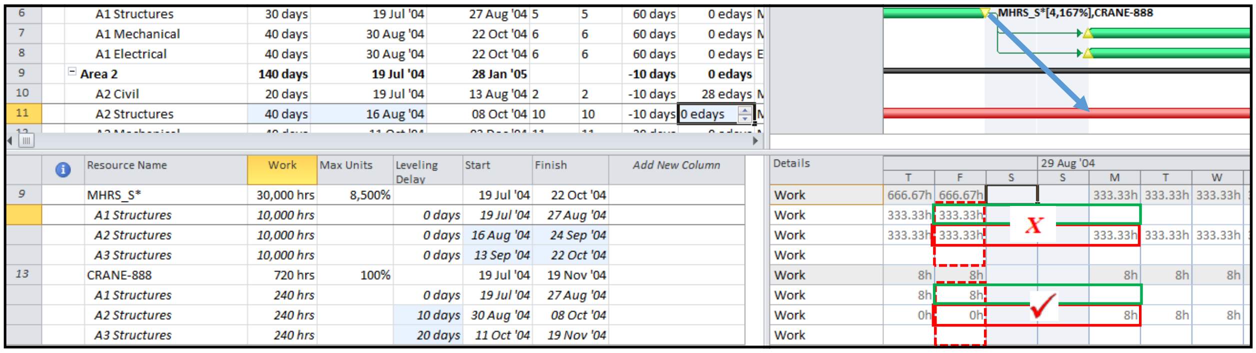


Figure 15: Inferred Resource Driver Link – A1/A2 Structures w/ Assignment Leveling

Similar analyses of the remaining 7 tasks with explicit task leveling delay results in identification of the following resource driver links (Figure 16 through Figure 22):

- A2 Electrical to A2 Electrical Change Order;
- A2 Civil to A3 Civil;
- A2 Structures to A3 Structures;
- A3 Install Line A to A3 Install Line B;
- A3 Install Line B to A3 Install Line C;
- A3 Install Line C to A3 Install Line D;
- A3 Install Line D to A3 Install Line E.

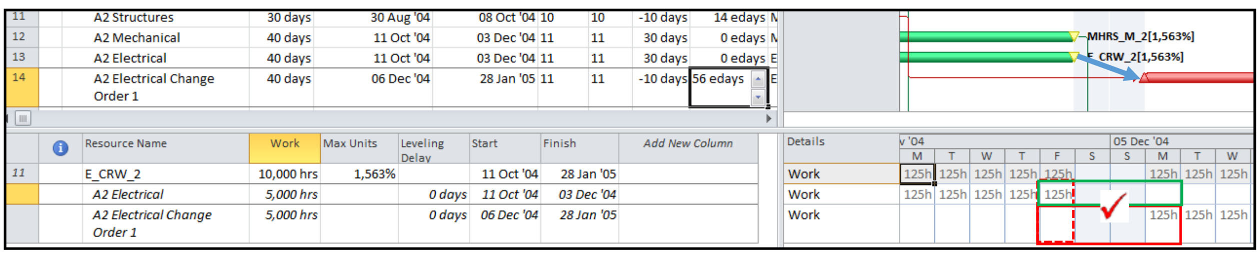


Figure 16: Inferred Resource Driver Link – A2 Electrical to A2 Electrical CO

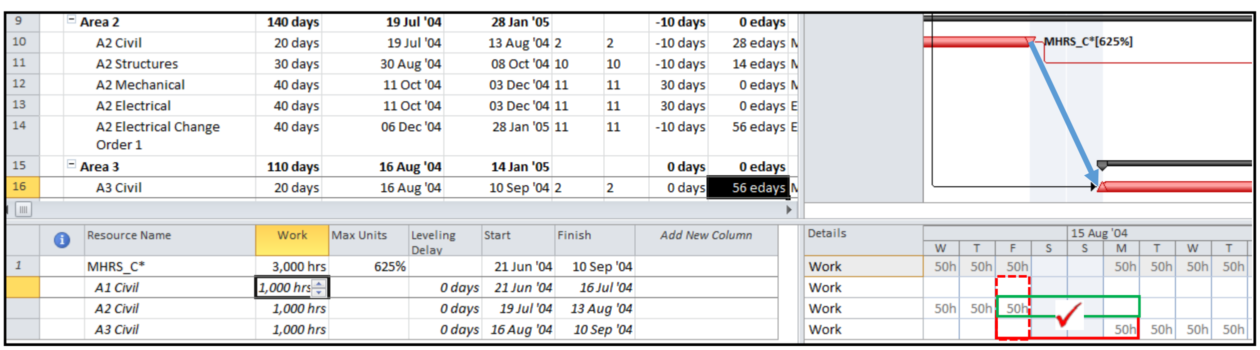


Figure 17: Inferred Resource Driver Link – A2 Civil to A3 Civil

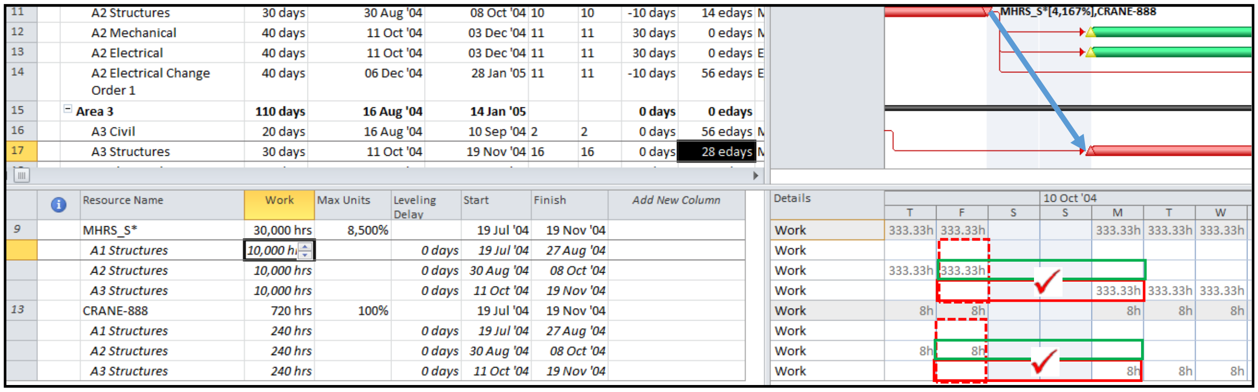


Figure 18: Inferred Resource Driver Link – A2/A3 Structures (No Assignment Leveling)

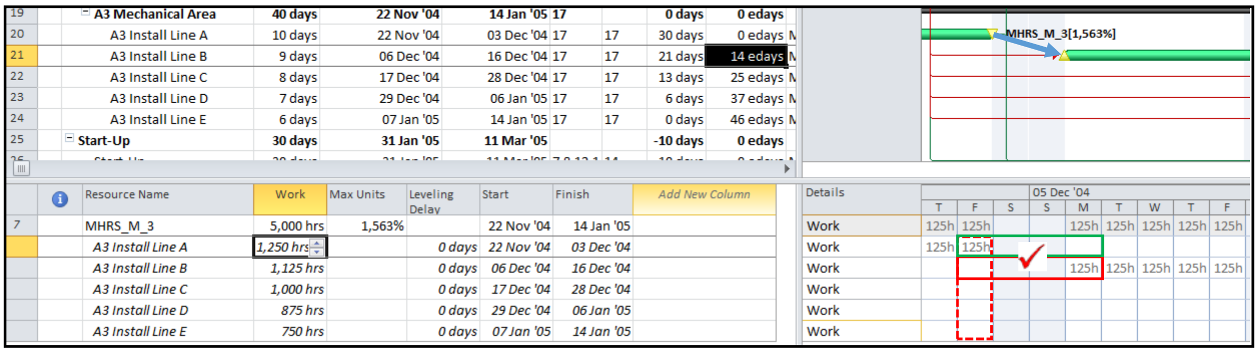


Figure 19: Inferred Resource Driver Link – A3 Install Line A to A3 Install Line B

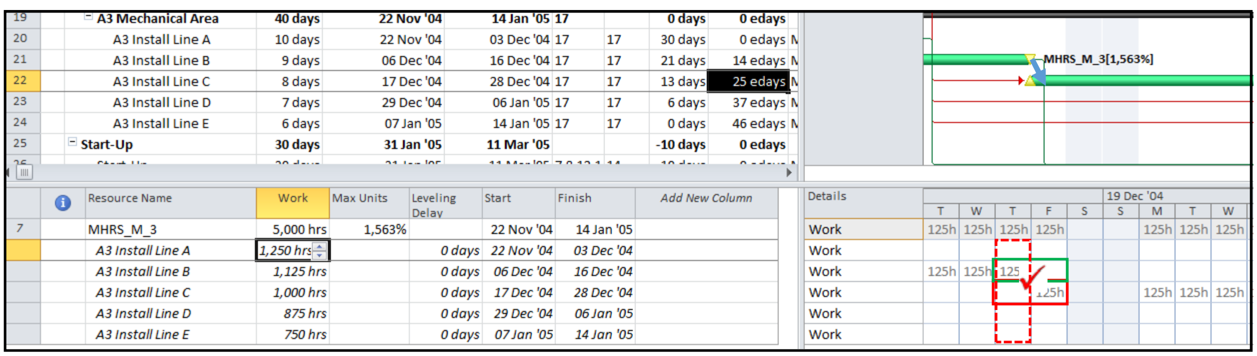


Figure 20: Inferred Resource Driver Link – A3 Install Line B to A3 Install Line C

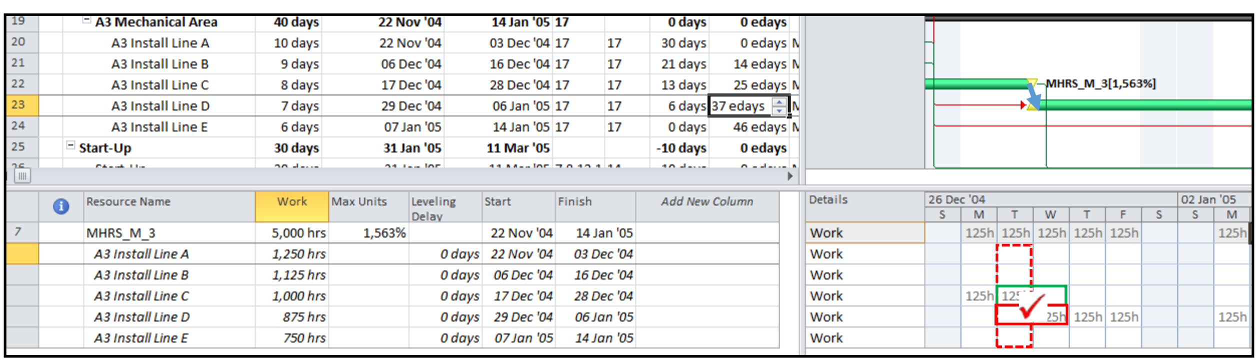


Figure 21: Inferred Resource Driver Link – A3 Install Line C to A3 Install Line D

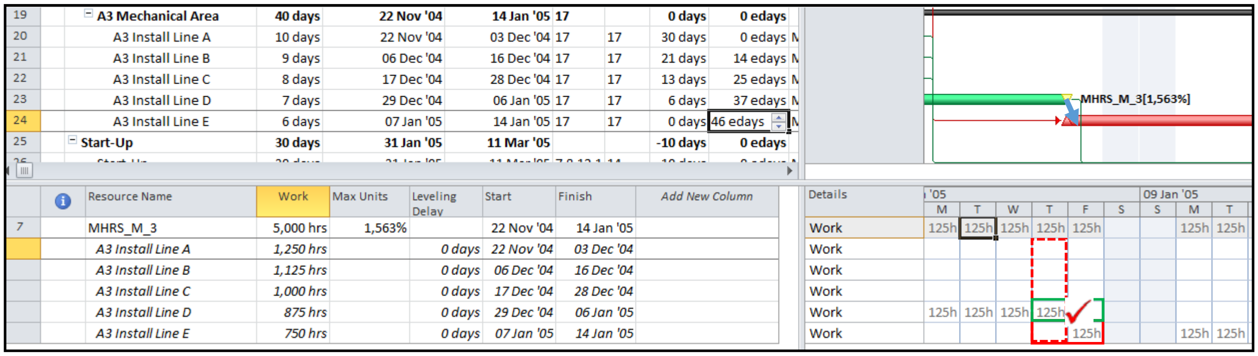


Figure 22: Inferred Resource Driver Link – A3 Install Line D to A3 Install Line E

5.0 INTEGRATED LOGIC TRACING

Resource-driving links that are inferred using the described procedure can be readily incorporated into existing logic tracing routines for both forward-pass and backward-pass logic analysis of MSP schedules. Results shown here have been derived using BPC Logic Filter, an MSP add-in that was previously developed by the author for internal use. Among other things, the add-in determines and aggregates relationship free floats along the various logical paths leading to a milestone, grouping and color-coding the results by the aggregated "path relative float" values.

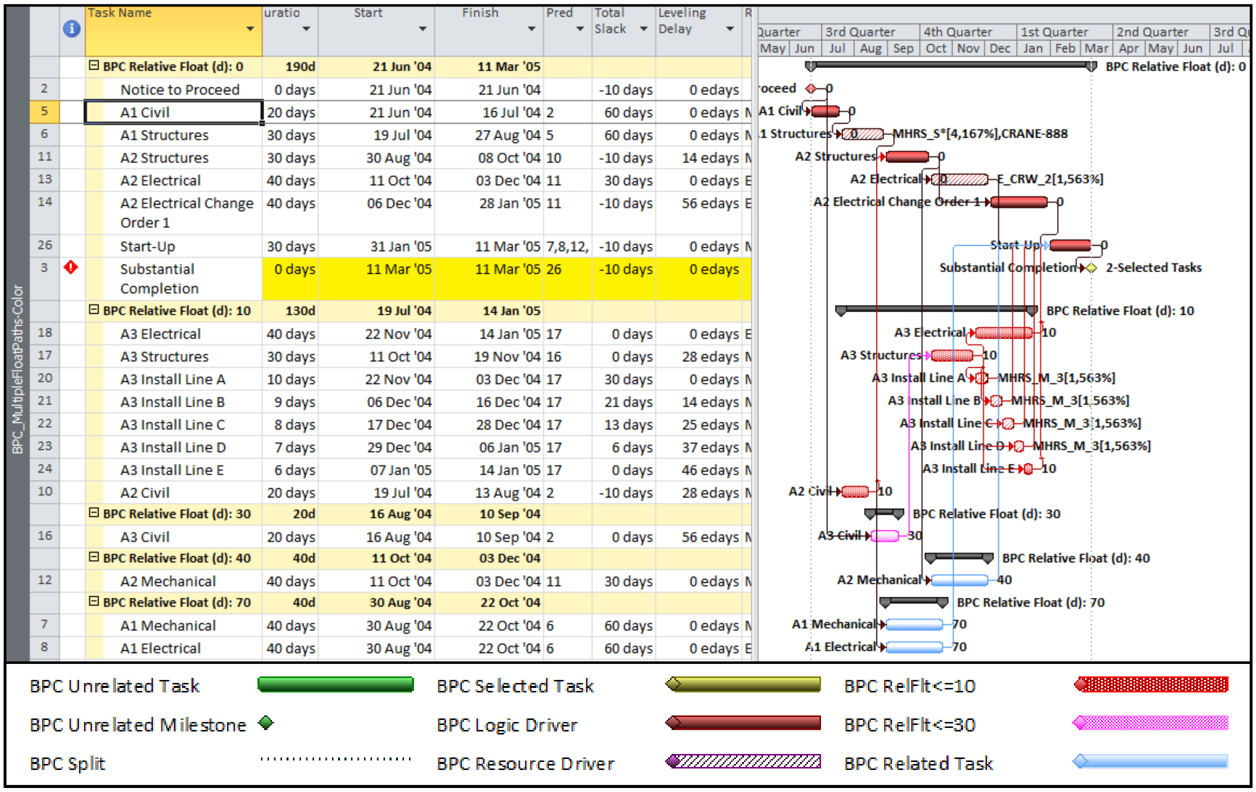
Using the add-in, the driving and non-driving logic paths to substantial completion were explored while automatically determining and incorporating the nine inferred resource-driving links listed above. Due to the method of their calculation, resource-driving links are assumed to have a relationship free float of zero. The resulting resource-constrained multiple float paths to substantial completion are displayed in Figure 23[7]. As shown in the figure, the resource constrained driving path to substantial completion of the leveled project (BPC Relative Float of 0d) begins with A1 Civil and A1 Structures. The latter task must finish (releasing resources) before A2 Structures can start. A2 Electrical can proceed when structures are in place, but it must finish (releasing resources) before A2 Electrical Change Order can start. Finally, the Start-up proceeds according to its driving logical link after completion of all its predecessors.

In contrast to Figure 9 above which was based on total slack, Figure 23 demonstrates the following:

1. There is a clearly defined, unbroken, resource-constrained driving (critical) path extending from start to completion of the leveled project.
2. A lowest value for Total Slack does not necessarily indicate participation on the true (resource-constrained) critical path. For example, task A2 Civil has Total Slack of -10d (the same as some tasks on the critical path). With a path relative float of 10d, however, this task could slip 10 days without delaying the project.
3. A high value for Total Slack does not necessarily indicate non-participation on the true critical path. For example, tasks A1 Civil and A1 Structures have Total Slack of 60d, yet extension of either of these tasks will delay the project.

---

[7] MSP is not able to draw arrows depicting the inferred resource-driving logic links. The add-in instead depicts resource-driving tasks using cross-hatching on the bars.



	Task Name	uratio	Start	Finish	Pred	Total Slack	Leveling Delay	R
	⊟ BPC Relative Float (d): 0	190d	21 Jun '04	11 Mar '05				
2	Notice to Proceed	0 days	21 Jun '04	21 Jun '04		-10 days	0 edays	
5	A1 Civil	20 days	21 Jun '04	16 Jul '04	2	60 days	0 edays	N
6	A1 Structures	30 days	19 Jul '04	27 Aug '04	5	60 days	0 edays	N
11	A2 Structures	30 days	30 Aug '04	08 Oct '04	10	-10 days	14 edays	N
13	A2 Electrical	40 days	11 Oct '04	03 Dec '04	11	30 days	0 edays	E
14	A2 Electrical Change Order 1	40 days	06 Dec '04	28 Jan '05	11	-10 days	56 edays	E
26	Start-Up	30 days	31 Jan '05	11 Mar '05	7,8,12,	-10 days	0 edays	N
3	Substantial Completion	0 days	11 Mar '05	11 Mar '05	26	-10 days	0 edays	
	⊟ BPC Relative Float (d): 10	130d	19 Jul '04	14 Jan '05				
18	A3 Electrical	40 days	22 Nov '04	14 Jan '05	17	0 days	0 edays	E
17	A3 Structures	30 days	11 Oct '04	19 Nov '04	16	0 days	28 edays	N
20	A3 Install Line A	10 days	22 Nov '04	03 Dec '04	17	30 days	0 edays	N
21	A3 Install Line B	9 days	06 Dec '04	16 Dec '04	17	21 days	14 edays	N
22	A3 Install Line C	8 days	17 Dec '04	28 Dec '04	17	13 days	25 edays	N
23	A3 Install Line D	7 days	29 Dec '04	06 Jan '05	17	6 days	37 edays	N
24	A3 Install Line E	6 days	07 Jan '05	14 Jan '05	17	0 days	46 edays	N
10	A2 Civil	20 days	19 Jul '04	13 Aug '04	2	-10 days	28 edays	N
	⊟ BPC Relative Float (d): 30	20d	16 Aug '04	10 Sep '04				
16	A3 Civil	20 days	16 Aug '04	10 Sep '04	2	0 days	56 edays	N
	⊟ BPC Relative Float (d): 40	40d	11 Oct '04	03 Dec '04				
12	A2 Mechanical	40 days	11 Oct '04	03 Dec '04	11	30 days	0 edays	N
	⊟ BPC Relative Float (d): 70	40d	30 Aug '04	22 Oct '04				
7	A1 Mechanical	40 days	30 Aug '04	22 Oct '04	6	60 days	0 edays	N
8	A1 Electrical	40 days	30 Aug '04	22 Oct '04	6	60 days	0 edays	E

Figure 23: Resource-Constrained Near Longest Paths

6.0 LIMITATIONS/CLARIFICATIONS

6.1 Leveling Fringes

In the absence of substantial documentation, detailed examination of MSP leveling assignments indicates the following key leveling behaviors of MSP 2010 Professional:

1. Task assignments are not scheduled to start until ALL of the planned resources are available.
2. Resources are "transferred" from the predecessor task assignment to the successor task assignment with no time delay and no overlap. There is, in other words, no leveling fringe.

The proposed method for inferring resource-driving links is based on these behaviors, even though they appear inconsistent with real-world management practices. For example, if an assignment requires ten workers while only nine are available, it is likely that the foreman would progress the work rather than allow workers to be idled.

If future editions of MSP were to modify these leveling behaviors, than revision of the method would be required.

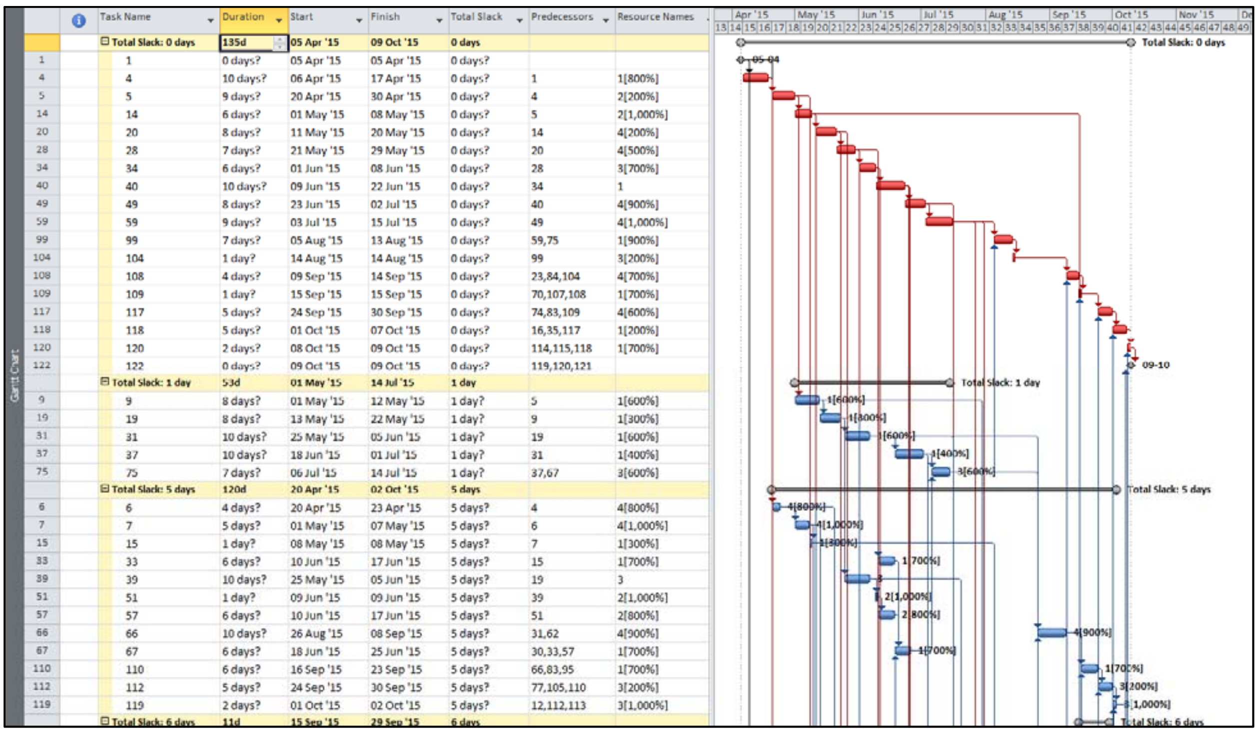
6.2 Standard Project Results

The method described above was tested on two benchmark project schedules taken from the PSPLIB project scheduling library [9, p. 205]. This library was developed specifically for testing resource-constrained scheduling algorithms. Both schedules were leveled using the standard options of Figure 7 before logic tracing.

6.2.1 PSPLIB J1201_7

PSPLIB J1201_7 is a 120-task project (not counting start and finish milestones) with completely closed logic comprising 183 relationships. There are 4 resources, each with a maximum availability of 11 to 13 units (i.e. 1,100 to 1,300%.) Each task has a single resource assignment (120 assignments total), typically comprising a partial workload (1 to 10 units) of one of the four available resources.

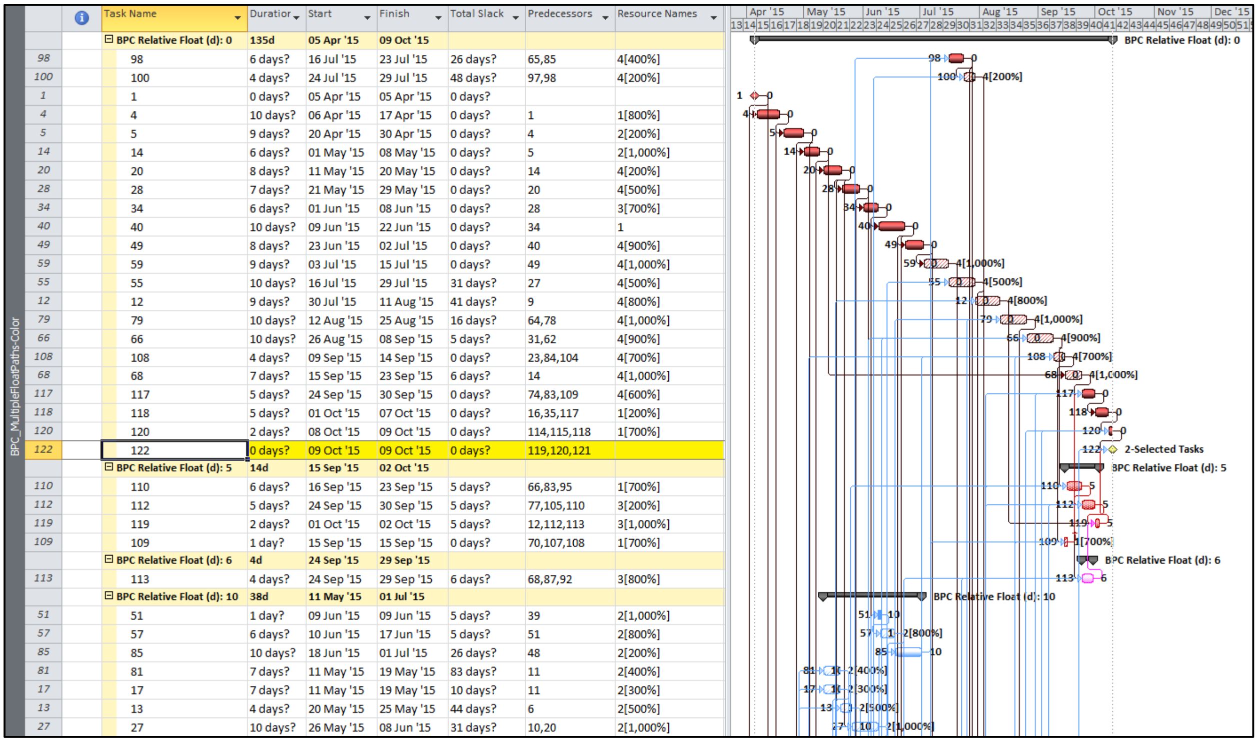
As determined by Total Slack, Figure 24 illustrates a critical path that is primarily logic driven for the first half of the project, after which substantial gaps related to the leveling delays come into play.



	Task Name	Duration	Start	Finish	Total Slack	Predecessors	Resource Names
	Total Slack: 0 days	135d	05 Apr '15	09 Oct '15	0 days		
1	1	0 days?	05 Apr '15	05 Apr '15	0 days?		
4	4	10 days?	06 Apr '15	17 Apr '15	0 days?	1	1[800%]
5	5	9 days?	20 Apr '15	30 Apr '15	0 days?	4	2[200%]
14	14	6 days?	01 May '15	08 May '15	0 days?	5	2[1,000%]
20	20	8 days?	11 May '15	20 May '15	0 days?	14	4[200%]
28	28	7 days?	21 May '15	29 May '15	0 days?	20	4[500%]
34	34	6 days?	01 Jun '15	08 Jun '15	0 days?	28	3[700%]
40	40	10 days?	09 Jun '15	22 Jun '15	0 days?	34	1
49	49	8 days?	23 Jun '15	02 Jul '15	0 days?	40	4[900%]
59	59	9 days?	03 Jul '15	15 Jul '15	0 days?	49	4[1,000%]
99	99	7 days?	05 Aug '15	13 Aug '15	0 days?	59,75	1[900%]
104	104	1 day?	14 Aug '15	14 Aug '15	0 days?	99	3[200%]
108	108	4 days?	09 Sep '15	14 Sep '15	0 days?	23,84,104	4[700%]
109	109	1 day?	15 Sep '15	15 Sep '15	0 days?	70,107,108	1[700%]
117	117	5 days?	24 Sep '15	30 Sep '15	0 days?	74,83,109	4[600%]
118	118	5 days?	01 Oct '15	07 Oct '15	0 days?	16,35,117	1[200%]
120	120	2 days?	08 Oct '15	09 Oct '15	0 days?	114,115,118	1[700%]
122	122	0 days?	09 Oct '15	09 Oct '15	0 days?	119,120,121	
	Total Slack: 1 day	53d	01 May '15	14 Jul '15	1 day		
9	9	8 days?	01 May '15	12 May '15	1 day?	5	1[600%]
19	19	8 days?	13 May '15	22 May '15	1 day?	9	1[300%]
31	31	10 days?	25 May '15	05 Jun '15	1 day?	19	1[600%]
37	37	10 days?	18 Jun '15	01 Jul '15	1 day?	31	1[400%]
75	75	7 days?	06 Jul '15	14 Jul '15	1 day?	37,67	3[600%]
	Total Slack: 5 days	120d	20 Apr '15	02 Oct '15	5 days		
6	6	4 days?	20 Apr '15	23 Apr '15	5 days?	4	4[800%]
7	7	5 days?	01 May '15	07 May '15	5 days?	6	4[1,000%]
15	15	1 day?	08 May '15	08 May '15	5 days?	7	1[300%]
33	33	6 days?	10 Jun '15	17 Jun '15	5 days?	15	1[700%]
39	39	10 days?	25 May '15	05 Jun '15	5 days?	19	3
51	51	1 day?	09 Jun '15	09 Jun '15	5 days?	39	2[1,000%]
57	57	6 days?	10 Jun '15	17 Jun '15	5 days?	51	2[800%]
66	66	10 days?	26 Aug '15	08 Sep '15	5 days?	31,62	4[900%]
67	67	6 days?	18 Jun '15	25 Jun '15	5 days?	30,33,57	1[700%]
110	110	6 days?	16 Sep '15	23 Sep '15	5 days?	66,83,95	1[700%]
112	112	5 days?	24 Sep '15	30 Sep '15	5 days?	77,105,110	3[200%]
119	119	2 days?	01 Oct '15	02 Oct '15	5 days?	12,112,113	3[1,000%]
	Total Slack: 6 days	11d	15 Sep '15	29 Sep '15	6 days		

Figure 24: PSPLIB j1201_7 – Critical/Near-Critical Paths of Leveled Schedule, TS Basis

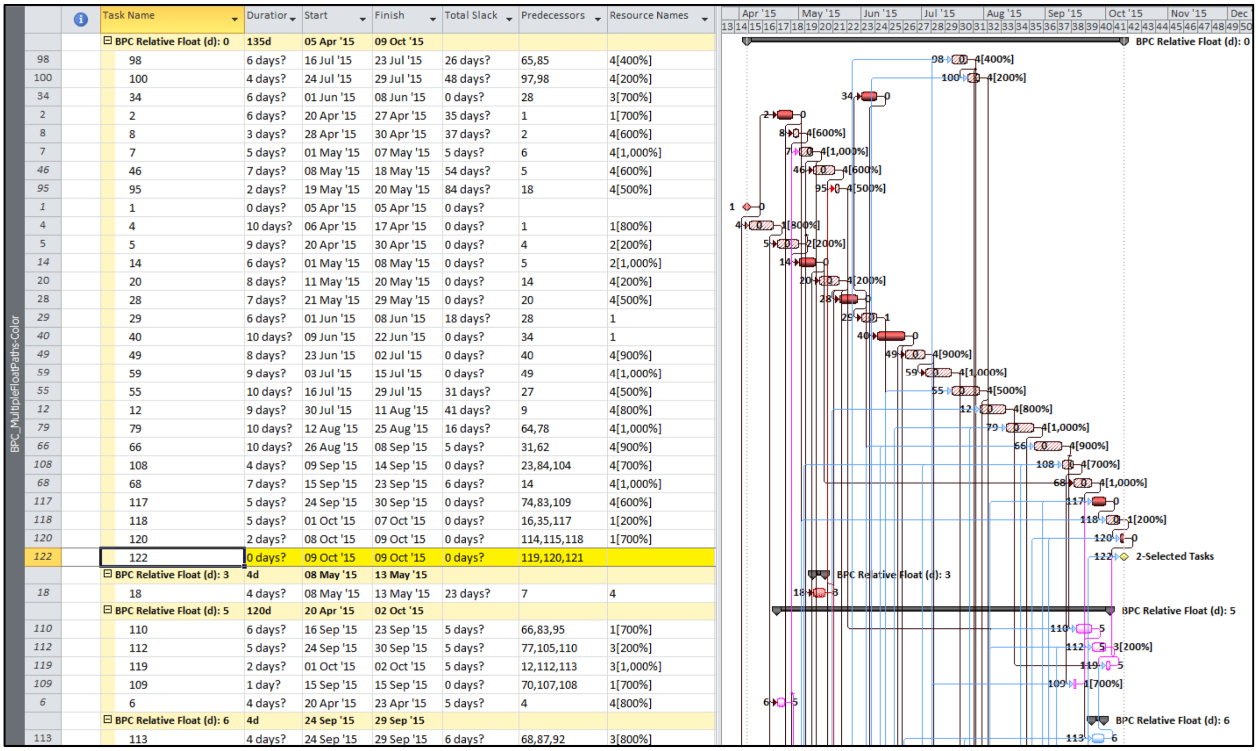
Figure 25 illustrates the resource-constrained near longest paths of the leveled schedule taking the inferred resource-driving links into play. A clearly defined longest path from project start to project completion is apparent, and the illustrated resource drivers appear reasonable. There is also a single parallel branch of the longest path; this arises from the fact that two tasks (55 and 100) release resource no. 4 at exactly the same time. As scheduled, extension of either of these tasks would lead to delay of the project, so the parallel branch appears correct.



	Task Name	Duration	Start	Finish	Total Slack	Predecessors	Resource Names
	BPC Relative Float (d): 0	**135d**	**05 Apr '15**	**09 Oct '15**			
98	98	6 days?	16 Jul '15	23 Jul '15	26 days?	65,85	4[400%]
100	100	4 days?	24 Jul '15	29 Jul '15	48 days?	97,98	4[200%]
1	1	0 days?	05 Apr '15	05 Apr '15	0 days?		
4	4	10 days?	06 Apr '15	17 Apr '15	0 days?	1	1[800%]
5	5	9 days?	20 Apr '15	30 Apr '15	0 days?	4	2[200%]
14	14	6 days?	01 May '15	08 May '15	0 days?	5	2[1,000%]
20	20	8 days?	11 May '15	20 May '15	0 days?	14	4[200%]
28	28	7 days?	21 May '15	29 May '15	0 days?	20	4[500%]
34	34	6 days?	01 Jun '15	08 Jun '15	0 days?	28	3[700%]
40	40	10 days?	09 Jun '15	22 Jun '15	0 days?	34	1
49	49	8 days?	23 Jun '15	02 Jul '15	0 days?	40	4[900%]
59	59	9 days?	03 Jul '15	15 Jul '15	0 days?	49	4[1,000%]
55	55	10 days?	16 Jul '15	29 Jul '15	31 days?	27	4[500%]
12	12	9 days?	30 Jul '15	11 Aug '15	41 days?	9	4[800%]
79	79	10 days?	12 Aug '15	25 Aug '15	16 days?	64,78	4[1,000%]
66	66	10 days?	26 Aug '15	08 Sep '15	5 days?	31,62	4[900%]
108	108	4 days?	09 Sep '15	14 Sep '15	0 days?	23,84,104	4[700%]
68	68	7 days?	15 Sep '15	23 Sep '15	6 days?	14	4[1,000%]
117	117	5 days?	24 Sep '15	30 Sep '15	0 days?	74,83,109	4[600%]
118	118	5 days?	01 Oct '15	07 Oct '15	0 days?	16,35,117	1[200%]
120	120	2 days?	08 Oct '15	09 Oct '15	0 days?	114,115,118	1[700%]
122	122	0 days?	09 Oct '15	09 Oct '15	0 days?	119,120,121	
	BPC Relative Float (d): 5	**14d**	**15 Sep '15**	**02 Oct '15**			
110	110	6 days?	16 Sep '15	23 Sep '15	5 days?	66,83,95	1[700%]
112	112	5 days?	24 Sep '15	30 Sep '15	5 days?	77,105,110	3[200%]
119	119	2 days?	01 Oct '15	02 Oct '15	5 days?	12,112,113	3[1,000%]
109	109	1 day?	15 Sep '15	15 Sep '15	0 days?	70,107,108	1[700%]
	BPC Relative Float (d): 6	**4d**	**24 Sep '15**	**29 Sep '15**			
113	113	4 days?	24 Sep '15	29 Sep '15	6 days?	68,87,92	3[800%]
	BPC Relative Float (d): 10	**38d**	**11 May '15**	**01 Jul '15**			
51	51	1 day?	09 Jun '15	09 Jun '15	5 days?	39	2[1,000%]
57	57	6 days?	10 Jun '15	17 Jun '15	5 days?	51	2[800%]
85	85	10 days?	18 Jun '15	01 Jul '15	26 days?	48	2[200%]
81	81	7 days?	11 May '15	19 May '15	83 days?	11	2[400%]
17	17	7 days?	11 May '15	19 May '15	10 days?	11	2[300%]
13	13	4 days?	20 May '15	25 May '15	44 days?	6	2[500%]
27	27	10 days?	26 May '15	08 Jun '15	31 days?	10,20	2[1,000%]

Figure 25: PSPLIB j1201_7 – Near-Longest Paths of Leveled Schedule, RF Basis, (Simple)

The analysis described earlier would infer resource-driving links only in the presence of explicit task leveling delay; this is a "simple" analysis. Extending the analysis to examine all resource assignments regardless of leveling delay can reveal latent resource drivers that are hidden because they occur concurrently (i.e. in parallel) with driving logical relationships. Such an analysis can exponentially increase computation time in a complex resource model. Figure 26 reveals two additional parallel branches of the resource constrained longest path as a result of the extended analysis. The figure also illustrates that when a task is both a resource driver and a logic driver, the add-in will highlight it as a resource driver on the bar chart.



ID	Task Name	Duration	Start	Finish	Total Slack	Predecessors	Resource Names
	BPC Relative Float (d): 0	135d	05 Apr '15	09 Oct '15			
98	98	6 days?	16 Jul '15	23 Jul '15	26 days?	65,85	4[400%]
100	100	4 days?	24 Jul '15	29 Jul '15	48 days?	97,98	4[200%]
34	34	6 days?	01 Jun '15	08 Jun '15	0 days?	28	3[700%]
2	2	6 days?	20 Apr '15	27 Apr '15	35 days?	1	1[700%]
8	8	3 days?	28 Apr '15	30 Apr '15	37 days?	2	4[600%]
7	7	5 days?	01 May '15	07 May '15	5 days?	6	4[1,000%]
46	46	7 days?	08 May '15	18 May '15	54 days?	5	4[600%]
95	95	2 days?	19 May '15	20 May '15	84 days?	18	4[500%]
1	1	0 days?	05 Apr '15	05 Apr '15	0 days?		
4	4	10 days?	06 Apr '15	17 Apr '15	0 days?	1	1[800%]
5	5	9 days?	20 Apr '15	30 Apr '15	0 days?	4	2[200%]
14	14	6 days?	01 May '15	08 May '15	0 days?	5	2[1,000%]
20	20	8 days?	11 May '15	20 May '15	0 days?	14	4[200%]
28	28	7 days?	21 May '15	29 May '15	0 days?	20	4[500%]
29	29	6 days?	01 Jun '15	08 Jun '15	18 days?	28	1
40	40	10 days?	09 Jun '15	22 Jun '15	0 days?	34	1
49	49	8 days?	23 Jun '15	02 Jul '15	0 days?	40	4[900%]
59	59	9 days?	03 Jul '15	15 Jul '15	0 days?	49	4[1,000%]
55	55	10 days?	16 Jul '15	29 Jul '15	31 days?	27	4[500%]
12	12	9 days?	30 Jul '15	11 Aug '15	41 days?	9	4[800%]
79	79	10 days?	12 Aug '15	25 Aug '15	16 days?	64,78	4[1,000%]
66	66	10 days?	26 Aug '15	08 Sep '15	5 days?	31,62	4[900%]
108	108	4 days?	09 Sep '15	14 Sep '15	0 days?	23,84,104	4[700%]
68	68	7 days?	15 Sep '15	23 Sep '15	6 days?	14	4[1,000%]
117	117	5 days?	24 Sep '15	30 Sep '15	0 days?	74,83,109	4[600%]
118	118	5 days?	01 Oct '15	07 Oct '15	0 days?	16,35,117	1[200%]
120	120	2 days?	08 Oct '15	09 Oct '15	0 days?	114,115,118	1[700%]
122	122	0 days?	09 Oct '15	09 Oct '15	0 days?	119,120,121	
	BPC Relative Float (d): 3	4d	08 May '15	13 May '15			
18	18	4 days?	08 May '15	13 May '15	23 days?	7	4
	BPC Relative Float (d): 5	120d	20 Apr '15	02 Oct '15			
110	110	6 days?	16 Sep '15	23 Sep '15	5 days?	66,83,95	1[700%]
112	112	5 days?	24 Sep '15	30 Sep '15	5 days?	77,105,110	3[200%]
119	119	2 days?	01 Oct '15	02 Oct '15	5 days?	12,112,113	3[1,000%]
109	109	1 day?	15 Sep '15	15 Sep '15	0 days?	70,107,108	1[700%]
6	6	4 days?	20 Apr '15	23 Apr '15	5 days?	4	4[800%]
	BPC Relative Float (d): 6	4d	24 Sep '15	29 Sep '15			
113	113	4 days?	24 Sep '15	29 Sep '15	6 days?	68,87,92	3[800%]

Figure 26: PSPLIB j1201_7 – Near-Longest Paths of Leveled Schedule, RF Basis, (Extended)

6.2.2 PSPLIB J12060_10

PSPLIB J12060_10 is a much denser 120-task project with completely closed logic comprising 257 relationships. This project has the same 4 resources, but their maximum availabilities are now increased from 11-13 units to 46-52 units. Each task has four resource assignments (480 assignments total), typically comprising a partial workload of one of four available resources. This project appears relatively challenging for a leveling algorithm, as it must prioritize among numerous parallel demands for partial workloads. During the simple analysis, the resource-constrained driving path contained 66 tasks arranged in 11 parallel paths, with 46 of these tasks identified as resource drivers. Repeating the analysis using the extended/parallel option revealed a resource-constrained driving path of 96 tasks, 95 of which were resource drivers, with no discernable logical paths. The overall 120-task project included only 9 tasks that were not resource drivers. The resulting chart was too large for legible presentation.

The situation described is one where a relatively small number of generic resources are fractionally divided among a large number of competing tasks. The resulting extensive concurrency seems to conflict with the underlying premise of the present work – that resource leveling decisions and preferential logic relationships can be used interchangeably. A true resource-constrained critical path in such circumstances seems of questionable value for project management.

6.3 Schedule Update Implications

As noted in the Introduction, resource leveling offers a relatively efficient response to out-of-sequence progress during schedule updates.

Figure 27 depicts the updated and re-leveled schedule of the prior example after a hypothetical three month period that witnesses the following events:

1. Area 1
   a. A1 Civil begins and finishes on time.
   b. A1 Structural commences as scheduled, but defective steel detailing causes the work to be suspended after 8 days. As of the new Status Date, the corrected steel is ready for erection.
   c. Mechanical and Electrical subcontractors mobilize to the site as originally scheduled and perform 1 day of prep work before pulling off pending completion of the steel.
2. Area 2
   a. The A2 Civil subcontractor starts on time but suspends the work after 2 days as a result of unforeseen conditions. He then moves on and completes Area 3.
3. Area 3
   a. A3 Civil starts and finishes early due to remobilization from Area 2.
   b. A3 Structural starts early due to availability of both site and resources. Presently it is 70% complete, with remaining duration of 9d.

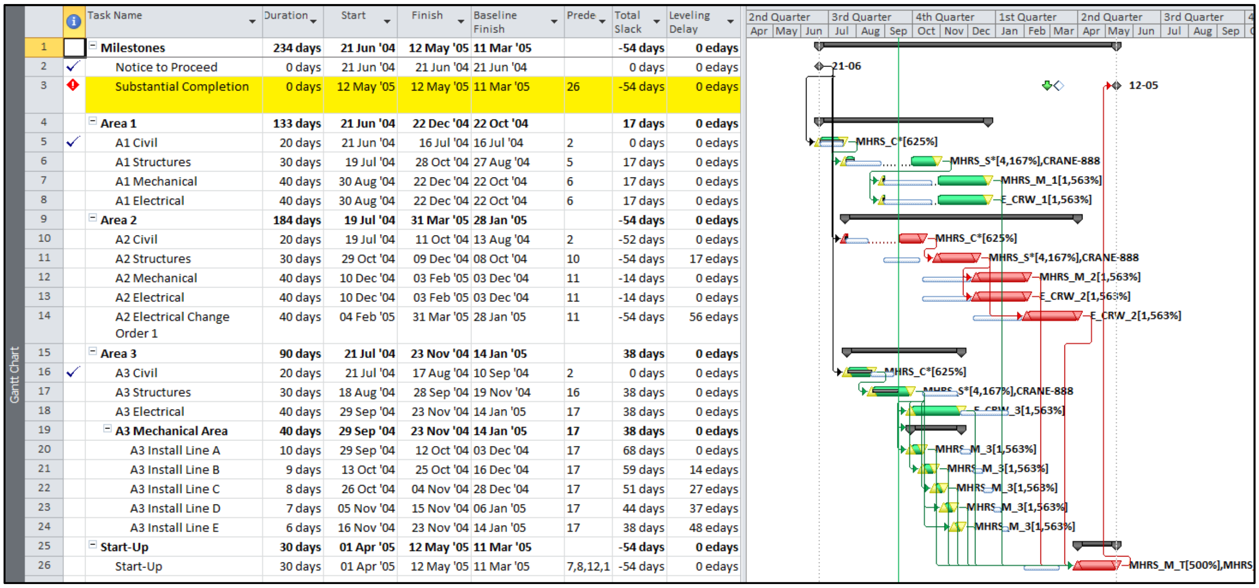
MSP's scheduling algorithm does not incorporate a true "Data Date," so progress updates leading to an accurate schedule forecast can be more complicated than in other software. Figure 27 reflects the following key steps:

1. Actual Start and Actual Finish dates are entered as appropriate.
2. For in-progress tasks, an Actual Duration is first entered, then the Remaining Duration computed by MSP is confirmed or modified. None have been modified here. (Actual and Remaining Duration indicate the complete and incomplete portions of the task's duration, without reference to a data date. MSP automatically creates a "Stop" date at the end of the Actual Duration and a "Resume" date at the beginning of the Remaining Duration.)
3. A new Status Date is applied, then the "Update Project" tool is used to re-schedule incomplete work to the right of the Status Date. For un-started tasks, "Update Project" imposes a Start-No-Earlier-Than constraint. For in-progress tasks, "Update Project" forces the Resume date to the first work period after the Status Date, thereby "splitting" the task. (See the A1 Structures and A2 Civil tasks.) If the "Split-in-progress-tasks" schedule option is turned off, however, the Resume date will not be moved. (As a result of this step, regularly updated MSP schedules can become riddled with constraints that are not related to prior planning processes. Careful documentation of true external constraints is required.)
4. The project is re-scheduled. With the "Split in-progress tasks" Schedule option still checked, MSP may further delay the "Resume" date to meet predecessor relationships. (See the A1 Mechanical and A1 Electrical tasks.) This is somewhat similar to "retained-logic" behavior in P6.
5. After confirming that incomplete and completed work are correctly separated by the Status Date line, the remaining work is re-leveled using the options shown in Figure 7.

While the original schedule (and leveling) was biased towards a top-to-bottom (A1 to A3) completion sequence, the following revised resource-leveling decisions are evident in the figure, as of the Status Date:

- A1 Structures may not resume until A3 Structures is complete and the structural resources are released back to Area 1.
- A2 Civil can resume immediately. Once it is complete, however, A2 Structures work must wait a further 17 elapsed days until the structural resources are finished with Area 1.

- Previously established resource drivers for the A2 Electrical Change Order 1 and the specialized A3 line installations remain unchanged, although the latter work is now accelerated compared to the original schedule.



	Task Name	Duration	Start	Finish	Baseline Finish	Prede	Total Slack	Leveling Delay
1	**Milestones**	**234 days**	**21 Jun '04**	**12 May '05**	**11 Mar '05**		**-54 days**	**0 edays**
2	Notice to Proceed	0 days	21 Jun '04	21 Jun '04	21 Jun '04		0 days	0 edays
3	Substantial Completion	0 days	12 May '05	12 May '05	11 Mar '05	26	-54 days	0 edays
4	**Area 1**	**133 days**	**21 Jun '04**	**22 Dec '04**	**22 Oct '04**		**17 days**	**0 edays**
5	A1 Civil	20 days	21 Jun '04	16 Jul '04	16 Jul '04	2	0 days	0 edays
6	A1 Structures	30 days	19 Jul '04	28 Oct '04	27 Aug '04	5	17 days	0 edays
7	A1 Mechanical	40 days	30 Aug '04	22 Dec '04	22 Oct '04	6	17 days	0 edays
8	A1 Electrical	40 days	30 Aug '04	22 Dec '04	22 Oct '04	6	17 days	0 edays
9	**Area 2**	**184 days**	**19 Jul '04**	**31 Mar '05**	**28 Jan '05**		**-54 days**	**0 edays**
10	A2 Civil	20 days	19 Jul '04	11 Oct '04	13 Aug '04	2	-52 days	0 edays
11	A2 Structures	30 days	29 Oct '04	09 Dec '04	08 Oct '04	10	-54 days	17 edays
12	A2 Mechanical	40 days	10 Dec '04	03 Feb '05	03 Dec '04	11	-14 days	0 edays
13	A2 Electrical	40 days	10 Dec '04	03 Feb '05	03 Dec '04	11	-14 days	0 edays
14	A2 Electrical Change Order 1	40 days	04 Feb '05	31 Mar '05	28 Jan '05	11	-54 days	56 edays
15	**Area 3**	**90 days**	**21 Jul '04**	**23 Nov '04**	**14 Jan '05**		**38 days**	**0 edays**
16	A3 Civil	20 days	21 Jul '04	17 Aug '04	10 Sep '04	2	0 days	0 edays
17	A3 Structures	30 days	18 Aug '04	28 Sep '04	19 Nov '04	16	38 days	0 edays
18	A3 Electrical	40 days	29 Sep '04	23 Nov '04	14 Jan '05	17	38 days	0 edays
19	**A3 Mechanical Area**	**40 days**	**29 Sep '04**	**23 Nov '04**	**14 Jan '05**	**17**	**38 days**	**0 edays**
20	A3 Install Line A	10 days	29 Sep '04	12 Oct '04	03 Dec '04	17	68 days	0 edays
21	A3 Install Line B	9 days	13 Oct '04	25 Oct '04	16 Dec '04	17	59 days	14 edays
22	A3 Install Line C	8 days	26 Oct '04	04 Nov '04	28 Dec '04	17	51 days	27 edays
23	A3 Install Line D	7 days	05 Nov '04	15 Nov '04	06 Jan '05	17	44 days	37 edays
24	A3 Install Line E	6 days	16 Nov '04	23 Nov '04	14 Jan '05	17	38 days	48 edays
25	**Start-Up**	**30 days**	**01 Apr '05**	**12 May '05**	**11 Mar '05**		**-54 days**	**0 edays**
26	Start-Up	30 days	01 Apr '05	12 May '05	11 Mar '05	7,8,12,1	-54 days	0 edays

Figure 27: Updated & Re-Leveled Schedule

Since the start of task A1 Structures and its assignments are actualized during the progress update, MSP cannot implement the required waiting time for this task using either a task or assignment leveling delay. Therefore these artifacts are not present in the schedule. Instead, MSP's leveling engine directly manipulates the task Resume date, delaying the incomplete part until resources are available. The resource-driving link in this case can only be inferred using the extended analysis previously mentioned, where each assignment part is examined in detail, regardless of the leveling delay artifacts. Presently, this is computationally intensive, though some streamlining of the algorithm seems possible.

Figure 28, generated using the extended analysis, illustrates the updated resource-constrained near longest paths of the project. As shown, the longest path includes the completed part of the A1 Structures split task and the incomplete part of the A2 Civil split task. It is desirable to exclude these parts from the display, but no technique to do so within the conventional MSP user interface is available.

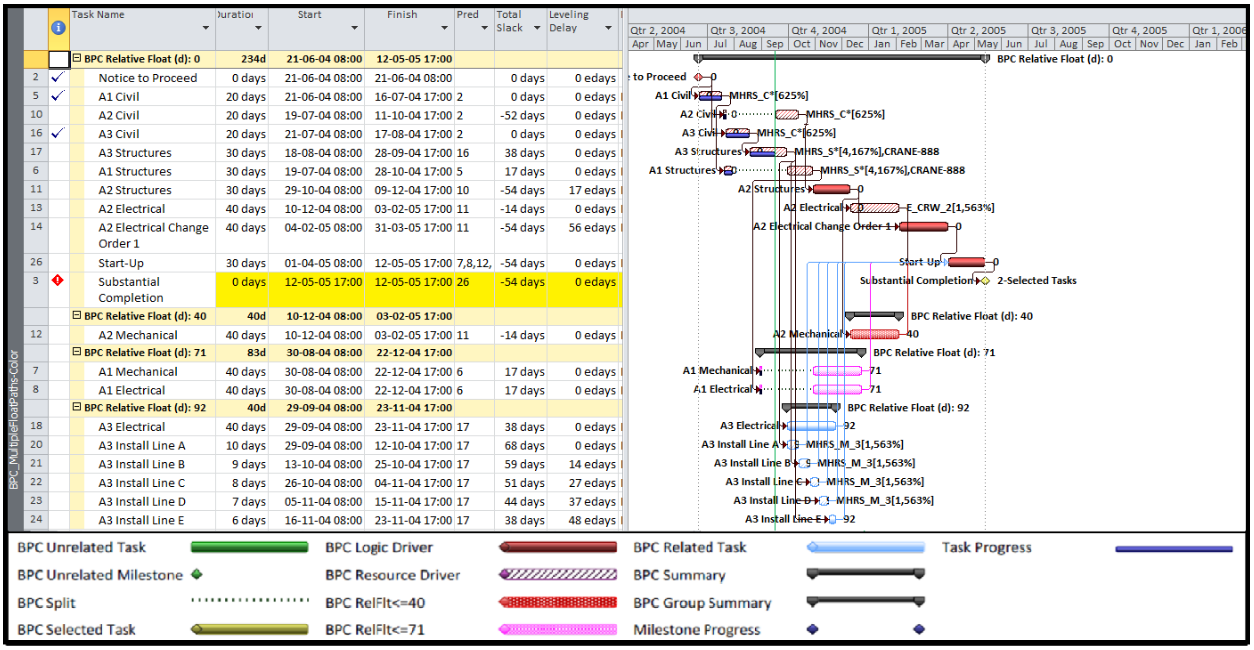


Figure 28: Updated and Re-Leveled Resource-Constrained Near Longest Paths

Where automatic resource leveling is incorporated as part of the schedule updating process, small deviations in work completion can lead to substantial changes in the sequences (and dates) of future work, especially if the leveling process is not guided by user-specified priorities. As a consequence, the overall work sequence for various resources can appear unstable or haphazard to various project stakeholders. The method described in this paper can be useful for highlighting, communicating, and justifying such changes as needed to optimize overall project schedule performance.

6.4 P6 Implications

Although P6 and MSP share certain CPM-focused features, the substantial differences in the underlying data architecture and software methodologies prevent direct and easy application of the described methods to a P6 schedule.

Regarding the inference of resource-driving links for incorporation into an existing logic tracing program, P6 offers the following advantages and disadvantages:

1. Resource assignments within P6 appear to be substantially simpler than MSP. Specifically, the time-scaled assignments appear to be dynamically calculated from just a few stored parameters. The automatic assignment splits that cause difficulties in an MSP project are not encountered, and comparison of competing assignments can be greatly simplified. (While P6's "Future Bucket Planning" feature provides the opportunity for manual assignment editing, the P6 leveler does not appear to do the same.)
2. Explicit and predictable artifacts of resource leveling (like "task leveling delay") are not found in the P6 database. Thus, the acute leveling delay of each task (or assignment) may first need to be computed directly using a brute-force approach to examine the logic-driven relationship free floats of the predecessor links.

3. As for MSP, either direct access to full "calendar math" functions (or the ability to fully mimic these functions in external software) is necessary to compute the free floats of logical relationships and assignments.

7.0 CONCLUSIONS

After resource leveling, Total Float becomes unreliable as an indicator of logic flow in a schedule. The resource-constrained critical path may then be successfully described by a driving-logic tracing algorithm that incorporates inferred resource-driving links. Aided by this information, the project manager can better focus on the resources and activities that ultimately drive the completion of the project.

The value of such a resource-constrained longest path is limited when resource loading and leveling is implemented in a way that stimulates randomized (rather than preferential) decision making on the part of the leveling software. Rather than relying solely on MSP's proprietary leveling rules, schedulers would be well advised to implement explicit leveling priorities that are consistent with the overall resource deployment plan for the project.

8.0 REFERENCES

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