THE DEVELOPMENT OF THE CONSTRUCTION ENGINEER: PAST PROGRESS AND FUTURE PROBLEMS[a]

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ABSTRACT: A retrospective view briefly traces graduate-level educational efforts that have resulted in the emergence of the construction engineer as a recognized member of the civil engineering profession. Then, a prospective view identifies four problem areas that relate to construction activities and should be of concern to civil engineers. These include the need for more effective implementation of new techniques, a reduction of disputes and litigation, improved contractual relationships, and professional teamwork that provides better results for the client. An example based on project scheduling and resource leveling is presented to relate and illustrate these problem areas. The example indicates that after 30 years of application of a "new" technique, a widespread lack of full understanding still leads to improper implementation, that this can lead to extended litigation, that contractual relationships create adversarial relationships in which many civil engineers are losing control to protect their clients, and that due to lack of teamwork by civil engineers in different specialities, prevention or mitigation of damages for the benefit of the client and the public is not being achieved.

INTRODUCTION

It is a great honor to be named the recipient of the Peurifoy Construction Research Award. This is especially true because I had the good fortune and pleasure to become acquainted with Professor Peurifoy while we both were visiting professors at a university in Santiago, Chile, in 1966. This award comes at a time when I have just retired from active teaching. My 35 years in the construction engineering and management graduate program at Stanford University spans the period from the first introduction of such a program in a major civil engineering department to the present. Therefore, this presentation offers an opportunity to note some of the progress that has been made in our field from an academic viewpoint and to suggest some areas that seem to me to need attention in the future.

LOOKING BACK

First, looking back, I believe that in the early 1950s there were considerable doubts whether a construction graduate program could or should be a part of a civil engineering curriculum. The subject matter was considered by some to be more closely related to the business schools or, by those less generous, to be trade-school material for the benefit of the skilled craftsman. There was doubt whether challenging subject matter could be developed for more than a couple of isolated courses. And, of importance to the admin-

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istrators in the top schools, there was great doubt whether significant research topics or support could be developed. There was often the feeling that graduates in the lower half of the class might opt for such programs if they were offered, but the more brilliant students, from an academic viewpoint, would certainly prefer the traditional areas of civil engineering education.

These concerns by now are largely behind us. Many major civil engineering departments have graduate programs in construction. Almost all the departments that are identified as the outstanding ones in the United States are also the ones that have outstanding graduate programs in construction. There are so many worthwhile courses that students must choose between them. Most of the major departments offer post-master programs leading to doctoral degrees and other advanced professional degrees. Significant research-contract volume involving challenging subjects is being performed. The Construction Division of ASCE is one of the Society's largest divisions. During a recent year, in preparation for an external review committee, I tabulated Graduate Record Examination (GRE) scores (quantitative plus verbal) for new students accepted in the various programs within our civil engineering department. The average for the construction students was the highest. So, it appears that we are not drawing second-rate applicants, in an academic sense. Our experience has been that this average graduate student is older, with several years of industry experience, which provides a greater challenge to the instructors and more valuable exposure for other students. Employers actively recruit construction students beginning about January of each academic year. We are well acquainted with one major construction company that in 1955 had no project managers with an engineering degree, but today all its project managers have engineering degrees.

In summary, construction education has come a long way just during the portion of my own teaching career at Stanford. I believe that ASCE deserves considerable credit for this. While other founder societies were shedding their manufacturing arms into other fields such as industrial engineering, our profession was willing to accept the fact that civil engineering construction was an integral part of the overall civil engineering process. The major universities deserve credit. Since 1955, our department has awarded construction master students the degree of master of science in civil engineering, with a further construction designation completely optional. The major universities have also recognized that a broad basic technical foundation is of such importance in civil engineering construction and heavy industrial construction that such programs are appropriately offered on the graduate level. The industry deserves credit as well for its helpful support. Support from our industrial affiliates program has probably been a major factor in our survival. The Business Roundtable and its creation, the Construction Industry Institute, has provided research focus and funding that has been very helpful. Our civil engineering department has the largest percentage of endowed chairs of our 10 engineering departments, and the majority of those chairs have origins in the construction industry.

Looking Ahead

The remainder of this paper is an attempt to identify some basic problems, in my opinion, of civil engineering construction that construction education

and research should address. The problems included here are very limited in number and include: (1) Implementation of new techniques; (2) litigation; (3) contractual relationships; and (4) professionalism. The discussion will reflect my own teaching areas, which have included a course in construction planning and scheduling and a course in legal and professional aspects of civil engineering. They also reflect some consulting experience in dispute-resolution procedures. A considerable part of civil engineering construction relates to public works, and most of my comments apply especially to this sector.

Rather than briefly cite many illustrations relating to the four basic problems that have been selected, I would prefer to develop an example involving a specific technique and use it as a basis for a more integrated discussion. Let's consider a simple exercise involving a small warehouse project introduced into my construction planning and scheduling class more than 25 years ago. The project is broken down into 30 activities, and sequential relationships, durations, and resource requirements for three resources are given. The students plot the network diagram and make the basic scheduling calculations for early and late start and finish dates and total and free float times. The resulting project duration is 28 days.

Next, the daily resource requirements for a schedule based on early start dates is generated. It indicates that one of the three resources, resource C, has an unfavorable (i.e., high and very irregular) daily requirement. At one point in the project as many as 20 units of this resource are needed. Maximum availability limits for the three resources are set, and the limit for resource C is four units. (Limits for the other two resources were such that they were met by the early start schedule.) Resource-leveling methods are discussed, and it is indicated that generally they are based on heuristic procedures that use priority rules. A set of simple rules is agreed upon, and the students manually level the schedule by following these rules mechanically. This provides an understanding of the process and indicates that, since no judgment is involved, a computer program could be written to do the same leveling. In this particular example, the students find that they can satisfy the resource limits in the same project time-span of 28 days, although this is a matter of good fortune since there is no assurance that the project duration might not have to be extended. The schedule now is a very tight one, and more will be said about this later.

Beginning in 1977, I added a "change order problem" to the warehouse example. This problem assumed that the project was subject to a contract clause, used by some government agencies, which defined total float and stated that any extensions of time under the various other contract clauses would "be granted only to the extent that equitable time adjustments for the activity or activities affected exceed the total float or slack along the channels involved." In the problem, a change order was issued at the beginning of the project, affecting a total of four activities and extending each of their durations. In each instance, the increase in duration was not only within the activity's total float period, but also within its free float period. Theoretically, delays within the free float period neither affect project duration nor delay any other activity. The project was still subject to the same resource availability limits as before. However, it was assumed that resource leveling had not been performed and that the contractor had submitted a conventional computer-produced schedule based on network sequential relationships and

estimated durations. Therefore, the project duration was still assumed to be 28 days.

According to the specifications, the contractor is entitled to no time extension for the change order. The students are asked to determine the project duration based on the changes in the four activities and the existing resource availability limits. Using the same procedure and priority rules as before, the project duration is found to have been extended to 50 days. Since the leveling procedures are heuristic ones, they do not guarantee an optimum result. For this problem, it can be shown by the resource-days required that no solution can be achieved in less than 47 days. When I free the students to eyeball a solution using judgment manipulations (but not changing activity durations or resource requirements), a few are able to obtain a 47-day solution. I also have them level both the original problem and the change order problem using one of the more powerful commercial software packages. The results obtained are 31 days and 52 days, respectively. An apparent reason for the poorer results is that even though this is a sophisticated program, it lacks the ability to interrupt activities that are interruptible. In any case, it is clear that in similar situations where both owner and contractor are not acquainted with the importance of the application of more advanced techniques, such as resource leveling, both a problem and a dispute are about to occur.

Using these simple classroom exercises as a base, we will further explore the four problem areas that were proposed for discussion.

Implementation of New Techniques

Networking techniques, such as CPM, PERT, Node Diagramming, and Precedence Diagramming, can hardly be called new techniques today. All have been around since the 1958–1964 period. But they offer examples of our failure to effectively implement techniques after they have been introduced. Consider the topic of resource leveling. Almost all construction projects are affected by the availability and economics of usage of resources. In most cases, the importance of resource leveling is a matter of reducing costs by avoiding peaks and valleys in daily requirements. However, in many cases it is essential because there are availability limits that must be met. Even where such limits don't exist initially, they can be introduced once decisions on plant and equipment capacities have been made or major purchases have occurred.

While resource-leveling techniques have been available since the early 1960s, for many years they were largely ignored in CPM applications. A schedule based on early start dates for each activity was generally issued. Such a schedule is almost always uneconomical and is often completely impossible. For example, in the warehouse project described earlier, the early start schedule required a peak of 20 units of resource C, but only four units were available. Extensive rescheduling was required to satisfy this limit. It is true that the project could still be done, in this instance, at its calculated duration of 28 days. However, had the original contract documents included the changes that were later made in the change order problem, the early start schedule would still have indicated a project duration of 28 days when actually 50 days were required to satisfy resource restrictions. Many contractors have complained that their attempts to use CPM during project performance have

failed because of a lack of support by the field personnel who must implement it. This would seem to be a natural result when uneconomical or impossible schedules have been issued for those field people to follow.

Even though resource-leveling programs are more prevalent today and no longer require a mainframe computer, their usage seems to occur mostly in the claims stage, after problems have occurred. The purpose of the change order problem was to demonstrate the dangers of not developing a realistic schedule at the outset. In this case, the contractor had submitted the conventional early start schedule with float values included. The specifications indicated that no time extensions would be granted where changes or delays only affected activities within their float periods. The changes made were all within the activity's float periods and, in fact, were within their free float periods. Because resource restrictions governed, the project was actually extended in duration by almost 80%. In such a situation, it is quite likely that neither contractor nor owner, in the absence of a resource-leveled schedule, would fully appreciate just why the project was gradually turning into a disaster.

This brings up another related problem. Few of even those who claim to be "CPM experts" fully appreciate the fact that in a resource-restrained schedule the concept of float breaks down and quite often the concept of a critical path breaks down. Since almost all construction projects are resource-restrained, at least to some extent, this becomes a source of major problems. The classic legal question in recent years, as well as the subject of numerous professional papers, is, "Who owns float time?" It is difficult to claim ownership of something that might not exist or that hasn't been quantified properly. These are fundamental matters that after 30 years still don't seem to be understood.

To illustrate this, consider the original warehouse project again. It was indicated that when resource limits were set for three resources used in this 30-activity project, the original early start schedule could be successfully rescheduled to meet the resource restrictions while, in this instance, maintaining the 28-day project duration. This rescheduling included splitting two interruptible activities, activities 5 and 8, into two portions each. Table 1 shows some data for the 30 activities in this project before and after leveling. Column two shows the conventional total float calculated for each activity. Fifteen of the 30 activities initially have zero float and, as indicated in column three, are critical. Column four shows the number of days by which the noncritical activities were rescheduled to a later start date to satisfy the resource restrictions. Since all of these changes used available float time, column five shows the total float that was not used and would be assumed to still exist.

A critical activity in a project can be defined as one that, if delayed, will delay project completion. Normally, these activities have zero total float and are part of paths through the project network composed solely of other critical activities. If they take longer to perform than their estimated duration the project will be delayed. If they are performed at their estimated duration but start late, the project duration also will be delayed. One reason for starting late is that sufficient resources are unavailable in the resource pool. These resources will only be available when activities using them are completed, and, therefore, those activities are able to release a sufficient number of the required resource units. Often those activities that must release resource units

TABLE 1. Resource Leveling Effects on Criticality Warehouse Project

Activity (1)	Total float before leveling (2)	Original critical (3)	Total float used in rescheduling (4)	Theoretical remaining total float (5)	Actual remaining total float (6)	Critical after leveling (7)
1	0	C	—	—	—	C
2	0	C	—	—	—	C
3	19	—	15	4	0	C
4	13	—	2	11	0	C
5A	9	—	0	9	0	C
5B	9	—	3	6	0	C
6	0	C	—	—	—	C
7	17	—	12	5	1	—
8A	14	—	7	7	0	C
8B	14	—	9	5	1	—
9	0	C	—	—	—	C
10	5	—	0	5	5	—
11	0	C	—	—	—	C
12	0	C	—	—	—	C
13	2	—	0	2	0	C
14	0	C	—	—	—	C
15	5	—	0	5	0	C
16	0	C	—	—	—	C
17	5	—	1	4	0	C
18	0	C	—	—	—	C
19	5	—	1	4	0	C
20	0	C	—	—	—	C
21	5	—	1	4	0	C
22	0	C	—	—	—	C
23	5	—	1	4	0	C
24	0	C	—	—	—	C
25	0	C	—	—	—	C
26	5	—	1	4	3	—
27	0	C	—	—	—	C
28	5	—	4	1	0	C
29	4	—	4	0	0	C
30	0	C	—	—	—	C

may not be critical in the sense of having zero float. However, if they fail to release the resource units needed by a critical activity, they delay that activity and, hence, the project. Therefore, an activity having positive float can still be "resource critical," since it will delay project completion if it fails to release resources on time. In more complex networks, there may be several activities that release resources to the resource pool on a given date and, therefore, to a critical activity that needs some of these resource units from the pool. In these cases there may not be a single specific activity in the group that must release its units and that, therefore, can be identified as being "resource critical." In simple warehouse projects, one-to-one relationships existed and the resource-critical activities could be identified. They were activities that had to release needed resource units in order not to di-

rectly delay critical activities or not to delay other activities that, in turn, would delay critical activities.

Column six in Table 1 shows the actual remaining float time for those activities that had the positive remaining theoretical float times shown in column five. Note that for the 16 values involved, 12 are actually zero instead of positive and 15 of the 16 have less float than the theoretical float. All of these 12 additional critical activities were on network paths that were considered noncritical. As column seven indicates, this has become a very tightly scheduled project with almost every activity either time critical or resource critical. These results indicate the reasons why the change order problem, which only involved changes to activities within their float periods, actually extended the project duration from 28 days to 50 days.

More importantly, the results shown in these simple problems indicate that the conventional concepts of float time break down in a resource-constrained project. Float times may be much less than computed or may not exist at all, and project duration may not be determined by the conventionally calculated critical path. Again, since almost any construction project either must be resource-leveled to achieve a feasible solution or should be resource-leveled to achieve an economic solution, we have a problem that is almost always present but seems to be universally ignored. Some, and often many, of the conventional CPM data are not valid. The originally calculated network data, including float data, are useful as a basis for establishing and applying priority rules in heuristic leveling procedures. However, once leveling has been performed, float times may have little meaning.

A resource-critical activity is only critical based on the current leveled schedule. If its duration increases, project duration will increase if the job program remains the same. However, a new leveling run or a leveling run with different priority rules may produce a different job program, which may or may not show a longer project duration. Since it has not yet proved practical to use mathematically optimum solutions, we must depend on heuristic solutions whose results, in turn, depend on the particular "fit" that is achieved on a given leveling run. Thus a one-day delay of a resource critical activity might, if releveling were performed, produce a one-day project delay or no delay, or more than a one-day delay.

In summary, on this subject of implementation, I am using this example to say that, after 30 years, very few practitioners, or even those teaching the subject, seem to be aware of some of the basic shortcomings of widely used network scheduling techniques. Unrealistic specifications are used, disputes are created, and dispute resolution is often based on incorrect data. There are other areas of networking that would provide similar conclusions. There are undoubtedly similar examples from many other areas of construction engineering. We must not only use research in the scientific sense of creating new concepts, but, as engineers, we must continue research well into the implementation period. The United States has a reputation for inventing, then allowing others to reap the benefits of application. This is a poor reflection on the engineering profession. What bothers me even more is that techniques developed to allow engineers to reduce costs in construction are mostly being effectively implemented by others, after project completion and in the courtroom, to increase those costs. Possibly organizations like the Construction Industry Institute, with its short-range, application-oriented research, can fill the need for further studies directed towards achiev-

ing more effective results from concepts made available through basic research.

Litigation

Litigation, especially in public-works projects, has become so common that it is a major cost factor today. Competitive bidding for projects has always created an adversarial relationship. Owners want the most they can get from the lowest bidder, and contractors can furnish only what they must if they are to make a profit. Litigation often results from inequitable treatment by the owner, unrealistic contract documents, or from the low bidder's efforts to recoup losses resulting from an unrealistic bid.

In one sense, construction education has probably not helped this situation. The construction engineer with a graduate degree representing the contractor is often more knowledgeable in contract-administration matters than the engineer representing the owner. Civil engineers in about 50% of our universities do not even take a course in engineering law or in contracts and specifications. Few would take a course in scheduling or cost control. Yet their graduate-level construction counterparts often have taken a number of such courses. The result is twofold. The owner's engineers are likely to produce poor contract documents and make poor decisions on such matters as change orders and time extensions. The contractor's engineers are likely to recognize poor performance in these matters and have the capability to submit documents and lay groundwork that will justify and substantiate claims.

Litigation is not all bad. Besides correcting inequities, it often challenges the state of the art and encourages the use of more advanced practices by those who are able to learn from the painful experiences of others. What is a shame is so much time and money goes into efforts after the job has been completed when, if the same time and effort had been expended at the outset, the job would have been a great success for both owner and contractor.

I believe that the scheduling examples already presented, as well as those in the following discussion, provide some insight into several aspects of these statements.

Contractual Relationships

Contractual relationships, at least on the competitive-bidding scene, are becoming less viable. Consider another illustration using the scheduling examples. If the warehouse problem and the change order problem were combined (i.e., if the changes had been made before the original contract documents were issued) the conventional CPM calculations would still result in a project duration of 28 days. But resource restrictions, essentially resource C, would cause the duration to extend to 50 days after leveling had been performed. Assume that this is not a problem, since the owner has allowed a project duration of 52 days, and the contractor has been aware of the necessity to submit a resource-leveled schedule that meets availability limits.

Assume further that both parties realize that float values, based on the conventional CPM calculations, that produce the 28-day project duration, are no longer valid. Should changes be made by the owner or delays be caused by the owner, the effect on project duration can only be determined by performance of a releveling procedure, producing a new schedule that

will satisfy resource restraints. In such a case, the changes or delays might extend the project duration very little or not at all. From the contractor's viewpoint, it would be much more beneficial if such changes affected a conventional critical path having a 52-day duration, because the entire delay would cause a corresponding project delay. It would also be simple to establish entitlement to such a time extension.

In such a scenario, it is not difficult for contractors to ensure that this more desirable situation will exist. Under competitive-bidding requirements, the determining factor is price. On engineering construction, the contractor may submit a number of unit prices, realizing that some will be too low. But some will be probably be high. The contractor trusts that they will balance out to give a total price that is both competitive and achievable. But there is a definite control, set by competition, on how high the contractor can make those prices. After getting the job, the contractor is required to submit a CPM network involving time estimates for each activity, and often this submittal may not be required until, say, 90 days after the notice to proceed has been issued. Essentially, there is no control at this point on those time estimates. It is true that the owner's engineer reserves the right to approve the schedule. But unless it is clearly in the realm of the ridiculous, it would be very difficult for the owner's engineer to reject the contractor's values for activity time estimates, even when they appear "padded." Moreover, the contractor can argue that he or she is entitled to the full stated project duration to use as he or she sees fit.

Let me suggest a situation that provides a more significant example to civil engineers than the simple warehouse example. A major concrete gravity dam is to be constructed, consisting of 30 monoliths side by side, each having from 30 to 40 concrete lifts of, say, 5-ft depth. Included among many other activities in the contractor's network diagram are activities representing the preparation of each lift (stripping of forms from another lift, erection of forms, surface preparation, any reinforcing steel installation, etc.) and the placing of each lift. These two items alone produce about 1,000 activities. Assume that the owner has allowed 800 working days as project duration. The contractor selects a concrete delivery system, including batch plant and cableway capacities, to permit completion in 800 days.

The successful bidder is required to submit a network program in 90 days. When the diagram, based on physical and contractual restraints, is completed and time estimates are made, the conventional CPM calculations give a 500-day project duration, comparable to the 28-days for the warehouse. The reason is that, in the absence of any resource restrictions, lifts in all 30 monoliths might be placed concurrently. Actually there is a very real resource restriction, consisting of resource C, which now stands for concrete delivery. Only one concrete placement can be made at a time; those in the bottom of the monoliths take up to three days of round-the-clock placing, while near the crest it may be possible to place two lifts per day. Resource leveling gives an 800-day project duration, corresponding to the 50-day modified warehouse example. Since about 1,000 placements must be made in less than 800 days, each concrete placement becomes a resource-critical activity.

In this project network, there would be at least 30 basic paths (with interrelationships to other paths) that would follow through the 30 monoliths from bottom to top. All would have considerable float in the conventional sense, since none would be longer than 500 days, although the project du-

ration is 800 days. The contractor could declare all of these paths to be critical or near-critical, so in the event of changes that may already be anticipated, there will be no doubt of time-extension entitlement. Moreover, such extensions would be made on a one-for-one basis per day of delay, rather than on the results of a releveling solution that might produce a much lower figure. It is not difficult to achieve this objective. Since there are 30 to 40 lifts on each path, each day of additional time estimated for lift-preparation activities produces 30 to 40 days increase in path duration. It is not difficult to add seven to 10 days to each of these activities. What can be even more damaging is that the contractor can selectively choose which path to make time critical. This can be advantageous when, after 90 days into the project, the contractor recognizes paths that will likely be affected by owner changes that may be imminent, and paths that will probably result in contractor-caused delays.

My objective here is not to paint contractors as conniving rascals. Under existing public-works contractual relations they must be low bidder to obtain the contract, and they must protect their own interests in the process of completing it and staying whole. My point, rather, is that under existing contractual practices, the owner is losing control. Bid prices alone do not produce the most economical contract. Other factors that may prove very costly can now be established and quantified as the result of the development of more sophisticated techniques. Unless contractual relationships are modified to cope with these problems, more disputes and more litigation will result and will increase costs. The scheduling example used represents only a single problem area. Two solutions have already been proposed. One is the use of "no damage for delays" clauses. Another is to agree that all float belongs to the contractor and any owner changes will necessitate time extensions equal to the full time required for the change. Neither solution is realistic nor conducive to truly effective cost reduction.

Professional Relations

Early in this presentation, I commended the ASCE for recognition that construction, the manufacturing part of the profession, was an integral part of the overall civil engineering process. I also mentioned that our top civil engineering schools have recognized construction engineering and management as an appropriate graduate-level curriculum. While we have created a new professional group, we still have major problems, especially in public works, in creating professional relationships where both engineers representing the owners and those representing the contractors are working as a team to serve the interests of their clients.

In the medical profession, it is common that one doctor uses professional skills to diagnose a patient's problem and recommend a solution. Another doctor may be called on at that point to perform an operation. This surgeon is also a professional because he or she must be highly skilled to do his or her part of the process well and cope with unexpected problems that arise during the performance of the task. Both doctors are working for the patient's well-being. As patients, we hardly are willing to view the surgeon as little more than a skillful meat-slicer whom we should select on the basis of a low bid.

The relationship between owner, engineer, and contractor has become much

more similar to that between patient, doctor, and surgeon. We need to examine the methods that we use to contract for services. It is true that some years ago the Justice Department required ASCE to remove the ban on bidding for professional services from its Code of Ethics. However, I believe that the prevailing opinion of professional engineers still holds that factors other than price are more important in the award of a contract for professional services. We need a system that makes it reasonable for all the professionals involved in a construction contract to be working as a team to assure the owner of maximum benefit. We need more of a patient-doctor-surgeon relationship.

Consider again the dam example. A foundation problem is discovered under one of the dam monolith locations that will delay the work on that network path by 40 days. Assume that the contractor, as described earlier, has already ensured that the path involved will be time critical by adding several extra days to the estimates of the lift preparation times for about 40 concrete lifts. This was done as a practical matter of self-protection to ensure that all time originally available to the contractor was preserved. Time is money, and the contractor feels an obligation to his or her organization not to give anything away when under the cost pressure of a low-bid contract. The result is, therefore, a claim for a time extension of 40 days and extended overhead costs because of this delay. Assume the liquidated damages on the contract, which presumably reflect the owner's cost of late completion, are $20,000 per day and the contractor's extended overhead costs are $30,000 per day. The claim would cost the owner $2,000,000, plus the cost of the extra work involved.

The construction engineers in the contracting firm have the professional knowledge to do many things to mitigate damages from the unexpected. For example, time-cost trade-off concepts in network theory have been developed as a means of minimizing the costs that are associated with faster performance. In this case, their application is especially simple since there are about 40 activities on the critical path whose durations might each be decreased by one day with no effect on costs; time-cost trade-offs at zero cost are the best kind. Is the contractor unprofessional not to suggest this decision, which would reduce the cost to the owner by $2,000,000? It is highly improbable that the contractor's lawyers, who are considered professionals in our society, would propose such a solution. They would likely argue that entitlement to a 40-day time extension and payment of the full claim is the legal and proper settlement for this matter. It seems to me that this is wrong and that a system that can be used to justify such a viewpoint needs examination.

During more than 30 years of teaching a required undergraduate course on the legal aspects of civil engineering, I have championed the public-works competitive-bid system. It seems to be a logical approach in a free-enterprise system. While the owner is the public, contracts are awarded on its behalf by public officials who may lack statesmanlike qualities. The publicly opened low-bid approach keeps the system transparent and honest. It also furnishes a route for new enterprises to enter the system and grow.

However, it is increasingly apparent that the system is working poorly due to cross purposes, lack of team cooperation for the benefit of the owner or client, and resulting litigation. Disputes are prevalent and are costly and time-consuming for all parties. There are seldom any winners after these

disputes are settled except the lawyers and expert witnesses. Perhaps better bases for the award of contracts that consider matters in addition to price, without destroying the impartiality of our competitive bidding system, can be developed. For the past 20 years we have experimented with the use of professional construction management as another solution, with very mixed results. We also are trying to develop more effective dispute-resolution systems that attempt to avoid major litigation or arbitration at the end of the job. A lot remains to be done.

The important point is that during the past 35 years we have developed professional civil engineers for the construction phase, in addition to those already in the planning and design phases, of the process of bringing engineering projects from concept to reality. Now we must develop new working arrangements where these professionals are serving the public and other clients as a team, rather than being pitted at cross purposes. Probably no experience demonstrates this need as clearly as serving as an expert witness in a major contract dispute on a public-works project. Dispute resolution may go on for months or years. Rooms full of documents requiring computerized retrieval systems are often needed. And, often the efforts of well over 100 people, including lawyers, engineers, management, and staff, are required. The professionals involved often do their deepest thinking and produce their most profound and innovative results at this point when the project is completed. Much of the testimony is never read afterward by other professionals, and it may not even be available, and so it is largely lost to those who might implement it in future work. In summary, we have too many wasteful, adversarial proceedings with professionals lined up on both sides, instead of effective teamwork during the projects by those professionals whose skills could complement each other so well.

Conclusions

At the beginning of this presentation, I took a look backward at 35 years of teaching in a graduate program in construction engineering and management at Stanford to note the development of a new professional specialty in civil engineering, that of the construction engineer. Civil engineering is a very broad profession with many diverse parts, as may be noted by examining the numerous Technical Divisions in ASCE. Engineers in each division have specialized professional knowledge that is needed in the execution of civil engineering works. Except in very rare instances, these works require a combination of skills from not one but a number of these diverse Divisions. As new entities are recognized in a profession, existing approaches must become flexible or change in order that cooperative efforts are achieved to provide the highest service to the client. In the case of civil engineering and its emphasis on infrastructure works, the client is often the public.

Looking ahead, I cited four problem areas, mostly interrelated, that seem to me to deserve attention in furture teaching and research efforts. These were the implementation of research results, litigation, contractual relationships, and professional relations. A classroom problem was cited as a basis for introducing this discussion. It provided only very limited points of illustration, and many others could be made.

The implementation discussion cited a widely used technique in project planning, scheduling, and control, having some basic concepts that after 30

years are still not fully understood by those who apply them. This simple example is just one that is indicative of a much larger problem in American technology. We are good at developing new concepts but often lose our advantage when it comes to effective implementation. Unfortunately, this is a charge that falls in the realm for which engineering is responsible. Since construction is the "manufacturing" arm of civil engineering, directly responsible for much of the implementation effort in that field, it must face the challenge of this problem.

Failure to fully understand techniques that become widely used can lead to unrealistic specification requirements, performance problems that are poorly understood, and decisions for dispute resolution that are based on faulty reasoning. All of these tend to result in extended litigation, which has become so commonplace, especially in public-works projects.

Contractual relationships create adversarial roles between professionals when, instead, cooperative team efforts are needed to best serve the public and the client. Today, the construction engineer as a result of professional education often has a better understanding of contract administration and sophisticated management techniques than a civil engineer who represents the owner. The owner's engineer is losing some of his or her historical ability to exercise control. Placed in an adversarial role on competitively bid contracts, the contractor's engineer must look out for his or her own organization's well-being. On public works, the public is the one that most often suffers the results. Changes and new approaches are needed.

Our profession needs to create a structure where its members work cooperatively to serve both the public and its clients. Today, a new curriculum and a new body of research have evolved, providing ways by which the construction engineer can achieve better, more efficient, and less costly contract performance. Working as a team with other engineers, better design and constructability can be achieved, and adverse consequences of the unexpected during construction can be minimized. The construction engineer now, as a recognized professional civil engineer, shares the responsibility to establish a system where the planning, design, and building of civil engineering works are all accomplished in a manner that more nearly satisfies professional objectives.

The Fifth Peurifoy Construction Research Award

Presented at the American Society of Civil Engineers
1990 Annual Convention

November 1990



JOHN W. FONDAHL

CASE STUDY: THE WAREHOUSE PROJECT[1]

You are the successful contractor for a warehouse project. Based on the original bidding documents, you have developed the activity list shown in Table 1 which includes the activity number, the activity name, the activity duration, the set of predecessor activities, and the daily resource requirements.

The contract for this project requires completion within 28 working days after the *Notice to Proceed* and calls for liquidated damages for late completion at the rate of $1,000 per working day. The *General Conditions* of the contract include a clause identical to *SP-13* of the *U.S. Postal Service Specifications* (shown below). Following contract award, you submitted a computer printout of your master schedule that shows completion of the work in 28 working days.

At the time of the notice to proceed, the owner issues a *Change Order* and informs you that he has redesigned some of the work. This increases the duration of Activities 3, 7, 8, and 29 as follows:

Activity	Original Duration	New Duration	Duration Increase	Free Float (for comparison)
03-Fabricate interior wall partition [4C]	2d	8d	6d	15d
07-Fabricate exterior doors [2C]	2d	7d	5d	17d
08-Const. plywood ext. wall panel [4C]	3d	12d	9d	14d
29-Erect interior wall partitions [4C]	1d	4d	3d	4d

The owner agrees to pay the additional costs caused by the *Change Order* but refuses to allow any time extension. At this point, you become concerned about possible resource availability. **Each day you can only provide 4 carpenters (C), 4 ironworkers (I), and 4 laborers (L).**

Part 1

- Develop a schedule showing that you could complete the original project (before the *Change Order*) within 28 days without exceeding your resource availability constraints.
- Why do you think the owner denied granting the revised project any time extension?

Part 2

You now realize that you can no longer meet the 28-day schedule under the *Change Order* requirements. Thus, you accept the *Change Order* under protest, indicating that you do not agree with the owner's denial of time extension.

- How much time extension should you claim? Document your claim by producing a schedule using the revised activity duration estimates and subject to the above resource availability constraints. Knowing that this schedule will be challenged by the owner's top engineering talent, you must develop the shortest schedule possible.
- How much time extension should you claim if you could split activities?

Example 1: *General Services Administration* (GSA) Specification

"Adjustment of Contract Completion Time

The contractor acknowledges and agrees that actual delays in activities which, according to the computer-produced calendar-dated schedule, do not affect any contract completion date shown by the critical path in the network, do not have any effect on the contract completion date or dates and therefore will not be the basis for a change therein."

[1] Adapted by P.G. Ioannou from
"*Seabee Planner's and Estimator's Handbook*"
NavDocks-P-405, Dept. of the Navy, Bureau of Yards and Docks, Washington DC, circa 1960.

Example 2: *U.S. Postal Service* (USPS) Specification

"SP-13 Contractor-Prepared Network Analysis System* (NAS)*:

Float or slack is defined as the amount of time between the early start date, and the late start date, or the early finish date and the late finish date of any of the activities in the NAS schedule. Float or slack is not time for the exclusive use or benefit of either the Government or the Contractor. Extensions of time for performance required under the Contract General provisions entitled, "CHANGES", "DIFFERING SITE CONDITIONS", "TERMINATION FOR DEFAULT", "DAMAGES FOR DELAY", "TIME EXTENSIONS", OR "SUSPENSION OF WORK" will be granted only to the extent that equitable time adjustments for the activity or activities affected exceed the total float or slack along the channels involved."

TABLE 1. Activity List for Warehouse Project

MSP ID	P6 ID	Activity Name	Dur (d)	Predecessors	Resources
1	01	01-Site survey & material list	1		-
2	02	02-Material & equipment to site	3	1	-
3	03	03-Fabricate interior wall partition [4C]	2	2	4C
4	04	04-Fasten wood strips to purlins [2C]	2	2	2C
5	05	05-Fabricate timber trusses [4C]	4	2	4C
6	06	06-Excavate [4L]	1	2	4L
7	07	07-Fabricate exterior doors [2C]	2	2	2C
8	08	08-Const. plywood ext. wall panel [4C]	3	2	4C
9	09	09-Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	6	4C, 2I, 2L
10	10	10-Place drain pipes [SUB]	1	6	SUB
11	11	11-Pour footings [1C,2L]	1	9	1C, 2L
12	12A	12A-Cure & strip footings (start)	3	11	-
13	13	13-Erect steel cols & vert brace [4I]	1	12B	4I
14	14	14-Backfill, compact & grade slab [2L]	2	10,12B	2L
15	15	15-Erect trusses [4I]	1	13,5	4I
16	16	16-Forms, rebar & drains floor slab [4C,2I]	1	14	4C, 2I
17	17	17-Fab & erect frames @ truss pans [2C,2I]	1	15	2C, 2I
18	18	18-Pour slab [1C,2L]	1	13,16	1C, 2L
19	19	19-Erect steel purlins [4I]	1	4,17	4I
20	20	20-Cure slab	6	18	-
21	21	21-Place red bridging & weld [4I]	1	19	4I
22	22	22-Erect ext. wall panels [4C]	2	20,8	4C
23	23	23-Nail planks to purlins [2C]	2	21	2C
24	24	24-Erect doors [2C]	1	7,22	2C
25	25	25-Waterproof & insulate joints [2L]	1	22	2L
26	26	26-Lay tar paper on planks [2L]	1	23	2L
27	27	27-Paint ext. walls [SUB]	2	24,25	SUB
28	28	28-Erect corrugated roofing [2C]	2	26	2C
29	29	29-Erect interior wall partitions [4C]	1	3,20,26	4C
30	30	30-Cleanup [4L]	2	27,28,29	4L
31	12B	12B-Cure & strip footings (end) [1L]	1	12A	1L

MSP ID: Activity ID numbers to use in MS Project Pro (consecutive numbers).
P6 ID: Activity ID numbers to use in P6 Pro (similar to the numbers used by Fondahl, P3, and Suretrak).

Note: The original Warehouse Project had only 30 activities, but also specified the following for activity 12:

- "12 - Cure and strip footings"; T=4d; uses 1 Laborer, but only on the 4th day to strip the formwork.

This is modeled in Tables 1 & 2 by splitting activity 12 into two activities (with different resources) as follows:

- "12 or 12A - Cure and strip footings (start)"; T=3d (i.e., "Cure Footings"; no resources) and
- "31 or 12B - Cure and strip footings (end)"; T=1d (i.e., "Strip Footings"; 1L)

TABLE 2. Resource Leveling Effects on Criticality–Warehouse Project[1]

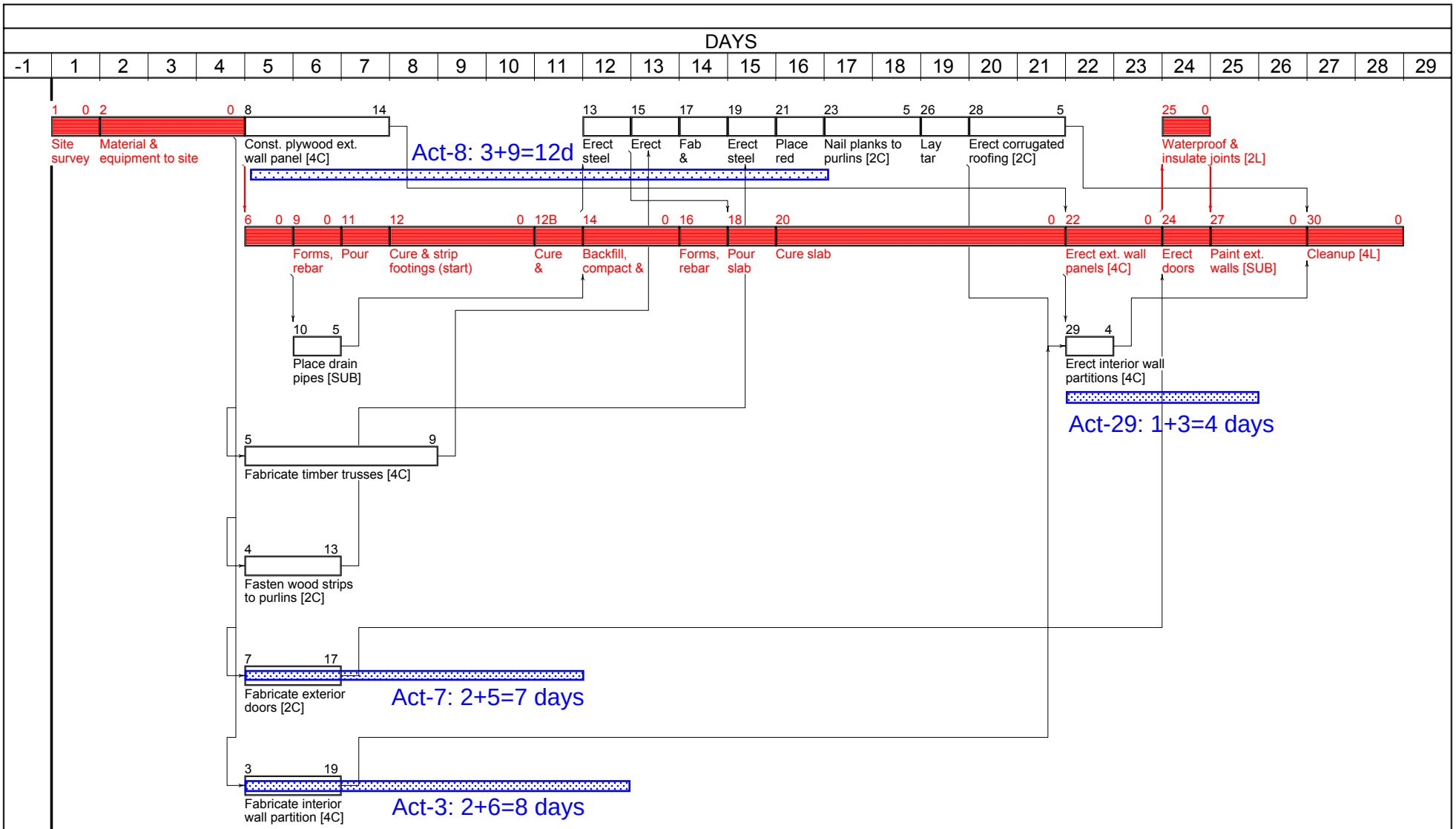
MSP Act ID (1)	P6 Act ID (1)	Total float before leveling (2)	Original critical (3)	Total float used in rescheduling (4)	Theoretical remaining total float (5)	Actual remaining total float (6)	Critical after leveling (7)
1	1	0	C	-	-	-	C
2	2	0	C	-	-	-	C
3	3	19	-	15	4	0	C
4	4	13	-	2	11	0	C
5 (1d)	5A (1d)	9	-	0	9	0	C
32 (3d)	5B (3d)	9	-	3	6	0	C
6	6	0	C	-	-	-	C
7	7	17	-	12	5	1	-
8 (1d)	8A (1d)	14	-	7	7	0	C
33 (2d)	8B (2d)	14	-	9	5	1	-
9	9	0	C	-	-	-	C
10	10	5	-	0	5	5	-
11	11	0	C	-	-	-	C
12 (3d)	12A (3d)	0	C	-	-	-	C
31 (1d)	12B (1d)	0	C	-	-	-	C
13	13	2	-	0	2	0	C
14	14	0	C	-	-	-	C
15	15	5	-	0	5	0	C
16	16	0	C	-	-	-	C
17	17	5	-	1	4	0	C
18	18	0	C	-	-	-	C
19	19	5	-	1	4	0	C
20	20	0	C	-	-	-	C
21	21	5	-	1	4	0	C
22	22	0	C	-	-	-	C
23	23	5	-	1	4	0	C
24	24	0	C	-	-	-	C
25	25	0	C	-	-	-	C
26	26	5	-	1	4	3	-
27	27	0	C	-	-	-	C
28	28	5	-	4	1	0	C
29	29	4	-	4	0	0	C
30	30	0	C	-	-	-	C

[1] Table 2 is a revised version of Table 1 from the paper:
Fondahl, J. (1991). "*The Development of the Construction Engineer: Past Progress and Future Problems*" J. Constr. Eng. Mgmt., ASCE, Vol 117, No 3, pp 380-392.

Main changes: In Table 2, each of the three activities 5, 8, and 12 has been split into two activities as follows:

Original Activity (Dur)		**Split MS Project Activities** (Dur)	**Split P6 Activities** (Dur)
5 (4d)	=	**5** (1d) + **32** (3d)	**5A** (1d) + **5B** (3d)
8 (3d)	=	**8** (1d) + **33** (2d)	**8A** (1d) + **8B** (2d)
12 (4d)	=	**12** (3d) + **31** (1d)	**12A** (3d) + **12B** (1d)

This enables MS Project and P6 (neither of which can split activities automatically when leveling resources) to "split" into two activities each of the three activities 5, 8, and 12, as described by Fondahl (1991).



Plot Date	19JUN03
Data Date	1JAN98
Project Start	1JAN98
Project Finish	28JAN98

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act id — inactive — tf

Activity Bar/Early Dates
Critical Activity
Progress Bar
Milestone/Flag Activity

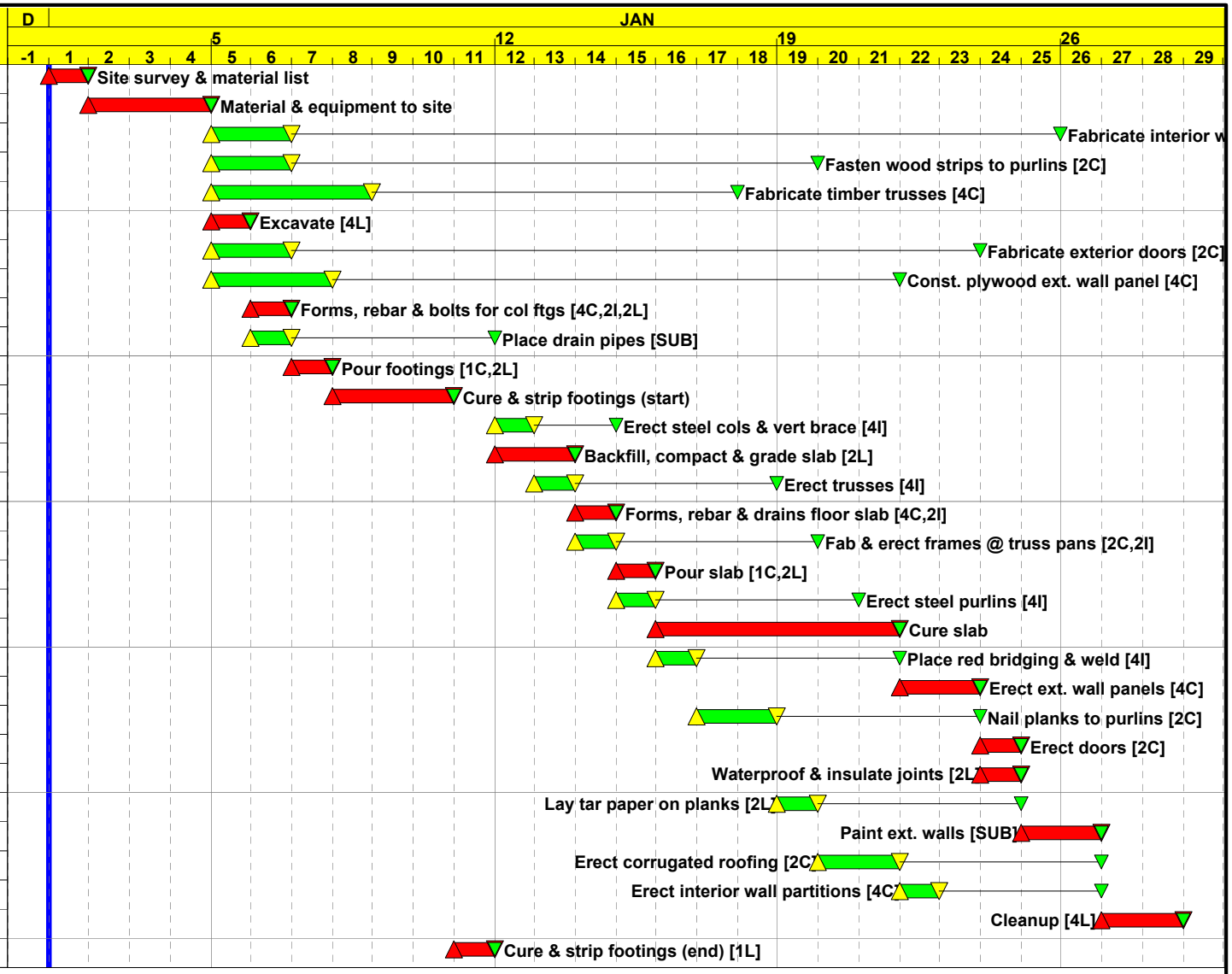
Sheet 1 of 1

P3 Time-Scaled Precedence Network
Duration: T = 28 days
Warehouse Project (Fondahl)

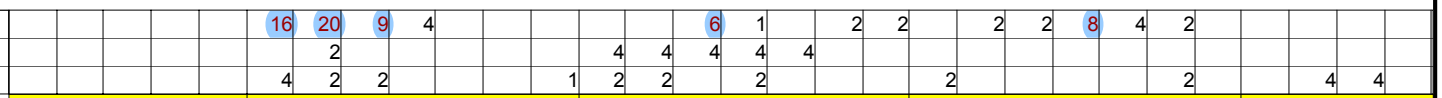
Early Start Schedule

Date	Revision	Checked	Approved

ID	Act	T	TF	FF
1	Site survey & material list	1	0	0
2	Material & equipment to site	3	0	0
3	Fabricate interior wall partition [4C]	2	19	15
4	Fasten wood strips to purlins [2C]	2	13	8
5	Fabricate timber trusses [4C]	4	9	4
6	Excavate [4L]	1	0	0
7	Fabricate exterior doors [2C]	2	17	17
8	Const. plywood ext. wall panel [4C]	3	14	14
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	0	0
10	Place drain pipes [SUB]	1	5	5
11	Pour footings [1C,2L]	1	0	0
12	Cure & strip footings (start)	3	0	0
13	Erect steel cols & vert brace [4I]	1	2	0
14	Backfill, compact & grade slab [2L]	2	0	0
15	Erect trusses [4I]	1	5	0
16	Forms, rebar & drains floor slab [4C,2I]	1	0	0
17	Fab & erect frames @ truss pans [2C,2I]	1	5	0
18	Pour slab [1C,2L]	1	0	0
19	Erect steel purlins [4I]	1	5	0
20	Cure slab	6	0	0
21	Place red bridging & weld [4I]	1	5	0
22	Erect ext. wall panels [4C]	2	0	0
23	Nail planks to purlins [2C]	2	5	0
24	Erect doors [2C]	1	0	0
25	Waterproof & insulate joints [2L]	1	0	0
26	Lay tar paper on planks [2L]	1	5	0
27	Paint ext. walls [SUB]	2	0	0
28	Erect corrugated roofing [2C]	2	5	5
29	Erect interior wall partitions [4C]	1	4	4
30	Cleanup [4L]	2	0	0
12B	Cure & strip footings (end) [1L]	1	0	0



Row	Group Name
1	Carpenters
2	Ironworkers
3	Laborers



Start Date 01JAN98
Finish Date 28JAN98
Data Date 01JAN98
Run Date 19JUN03 14:35

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Early Bar
Float Bar
Progress Bar
Critical Activity

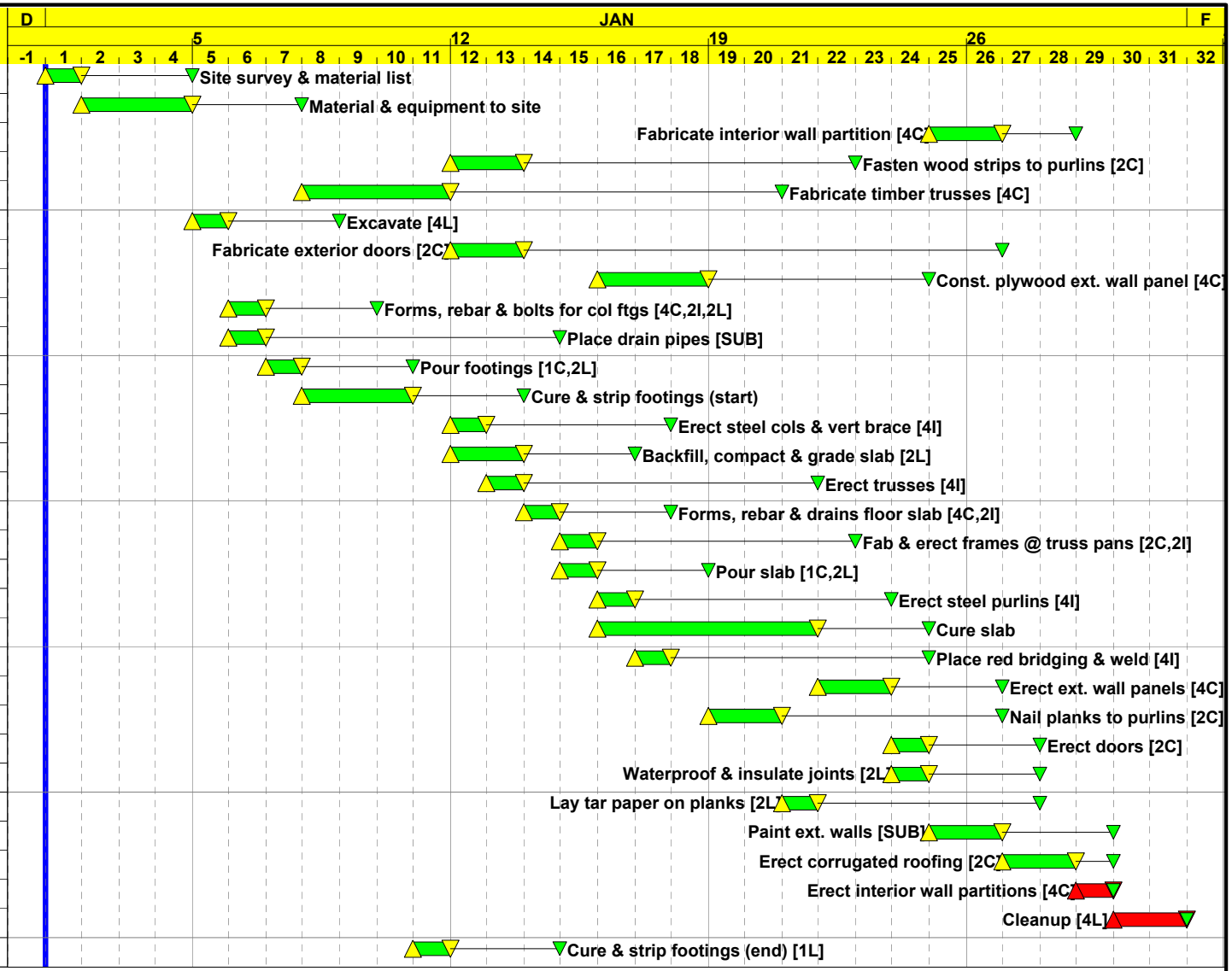
WARE Sheet 1 of 1

Warehouse Project (in P3)
28-day Orig. Schedule (Before Change Order)
Avail. Res.: 4Carpenters.,4Ironworkers, 4Laborers
Notice: Carpenters needed >> 4 Carp. available

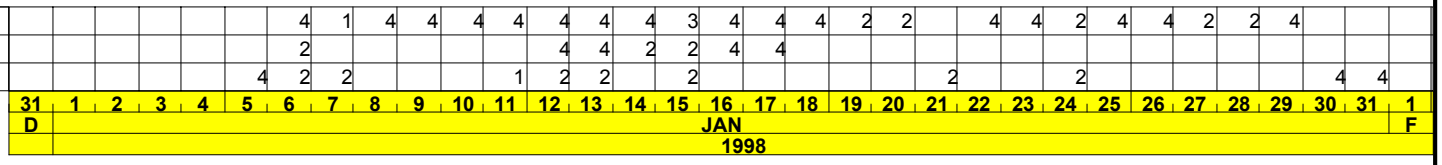
C.O. changes Act. Durations (dT):
T3 = 2 + 6 = 8 (dT=6 < FF=15)
T7 = 2 + 5 = 7 (dT=5 < FF=17)
T8 = 3 + 9 = 12 (dT=9 < FF=14)
T29 = 1 + 3 = 4 (dT=3 < FF=4)

Because all Change Order
dT < Avail. FF,
the project owner refuses
to grant any time extension.

ID	Act	T	TF	FF
1	Site survey & material list	1	3	0
2	Material & equipment to site	3	3	0
3	Fabricate interior wall partition [4C]	2	2	2
4	Fasten wood strips to purlins [2C]	2	9	2
5	Fabricate timber trusses [4C]	4	9	1
6	Excavate [4L]	1	3	0
7	Fabricate exterior doors [2C]	2	13	10
8	Const. plywood ext. wall panel [4C]	3	6	3
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	3	0
10	Place drain pipes [SUB]	1	8	5
11	Pour footings [1C,2L]	1	3	0
12	Cure & strip footings (start)	3	3	0
13	Erect steel cols & vert brace [4I]	1	5	0
14	Backfill, compact & grade slab [2L]	2	3	0
15	Erect trusses [4I]	1	8	1
16	Forms, rebar & drains floor slab [4C,2I]	1	3	0
17	Fab & erect frames @ truss pans [2C,2I]	1	7	0
18	Pour slab [1C,2L]	1	3	0
19	Erect steel purlins [4I]	1	7	0
20	Cure slab	6	3	0
21	Place red bridging & weld [4I]	1	7	1
22	Erect ext. wall panels [4C]	2	3	0
23	Nail planks to purlins [2C]	2	6	0
24	Erect doors [2C]	1	3	0
25	Waterproof & insulate joints [2L]	1	3	0
26	Lay tar paper on planks [2L]	1	6	5
27	Paint ext. walls [SUB]	2	3	3
28	Erect corrugated roofing [2C]	2	1	1
29	Erect interior wall partitions [4C]	1	0	0
30	Cleanup [4L]	2	0	0
12B	Cure & strip footings (end) [1L]	1	3	0



Row	Group Name
1	Carpenters
2	Ironworkers
3	Laborers



Start Date 01JAN98
Finish Date 31JAN98
Data Date 01JAN98
Run Date 19JUN03 15:18

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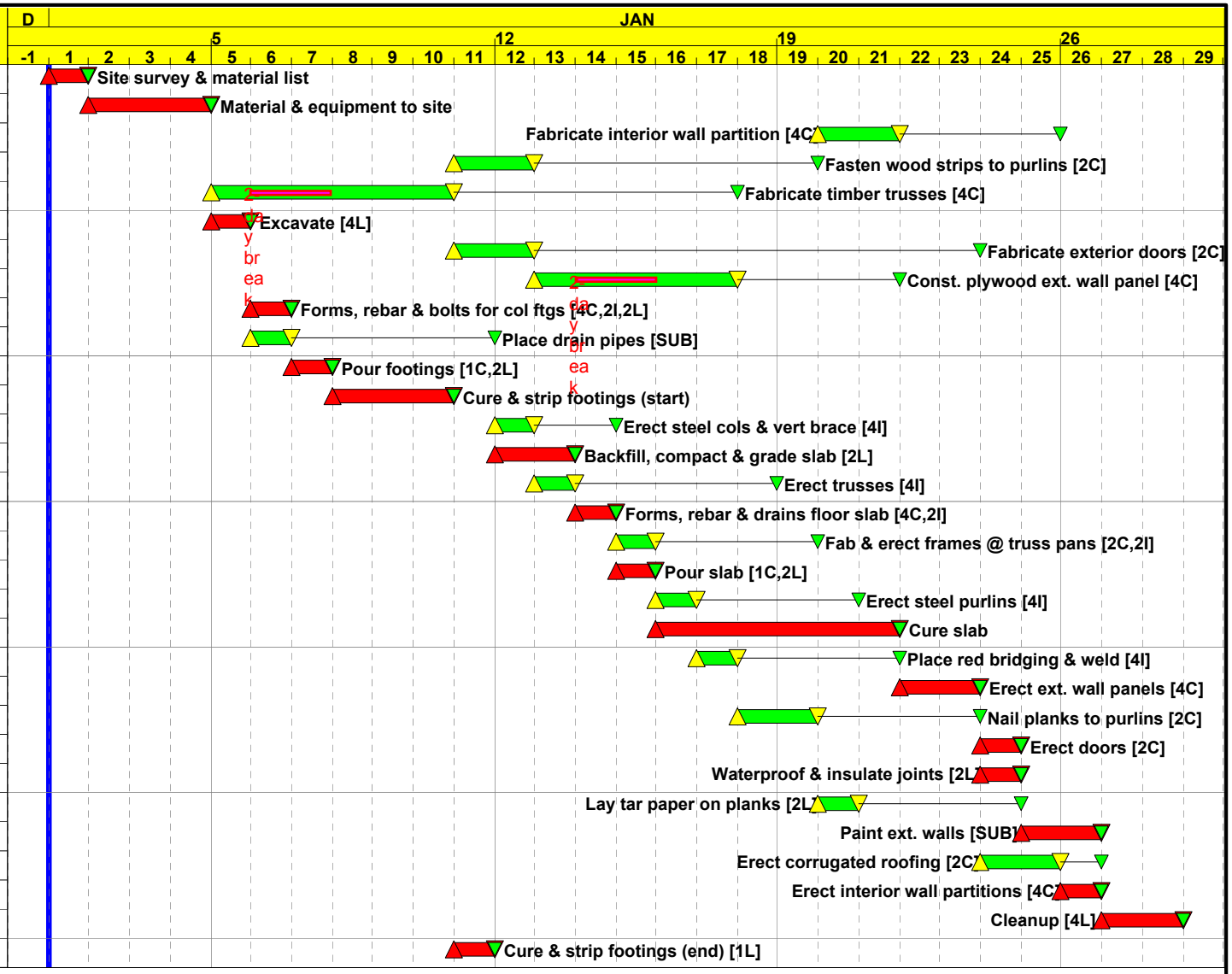
Early Bar
Float Bar
Progress Bar
Critical Activity

WARE Sheet 1 of 1

Warehouse Project
Original Activity Durations
Leveled by P3, No Splits: T=31 days

Fondahl found the same result using P3 and no splits

ID	Act	T	TF	FF
1	Site survey & material list	1	0	0
2	Material & equipment to site	3	0	0
3	Fabricate interior wall partition [4C]	2	4	4
4	Fasten wood strips to purlins [2C]	2	7	3
5	Fabricate timber trusses [4C]	4	7	2
6	Excavate [4L]	1	0	0
7	Fabricate exterior doors [2C]	2	11	11
8	Const. plywood ext. wall panel [4C]	3	4	4
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	0	0
10	Place drain pipes [SUB]	1	5	5
11	Pour footings [1C,2L]	1	0	0
12	Cure & strip footings (start)	3	0	0
13	Erect steel cols & vert brace [4I]	1	2	0
14	Backfill, compact & grade slab [2L]	2	0	0
15	Erect trusses [4I]	1	5	1
16	Forms, rebar & drains floor slab [4C,2I]	1	0	0
17	Fab & erect frames @ truss pans [2C,2I]	1	4	0
18	Pour slab [1C,2L]	1	0	0
19	Erect steel purlins [4I]	1	4	0
20	Cure slab	6	0	0
21	Place red bridging & weld [4I]	1	4	0
22	Erect ext. wall panels [4C]	2	0	0
23	Nail planks to purlins [2C]	2	4	0
24	Erect doors [2C]	1	0	0
25	Waterproof & insulate joints [2L]	1	0	0
26	Lay tar paper on planks [2L]	1	4	3
27	Paint ext. walls [SUB]	2	0	0
28	Erect corrugated roofing [2C]	2	1	1
29	Erect interior wall partitions [4C]	1	0	0
30	Cleanup [4L]	2	0	0
12B	Cure & strip footings (end) [1L]	1	0	0



Row	Group Name	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	Carpenters						4	4	1	4	4	4	4	4	4	4	3	4	4	2	2	4	4	4	4	4	2	4			
2	Ironworkers							2						4	4	2	2	4	4												
3	Laborers						4	2	2				1	2	2		2					2				2			4	4	

D 1997 — JAN 1998

Start Date 01JAN98
Finish Date 28JAN98
Data Date 01JAN98
Run Date 19JUN03 15:50

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Early Bar
Float Bar
Progress Bar
Critical Activity

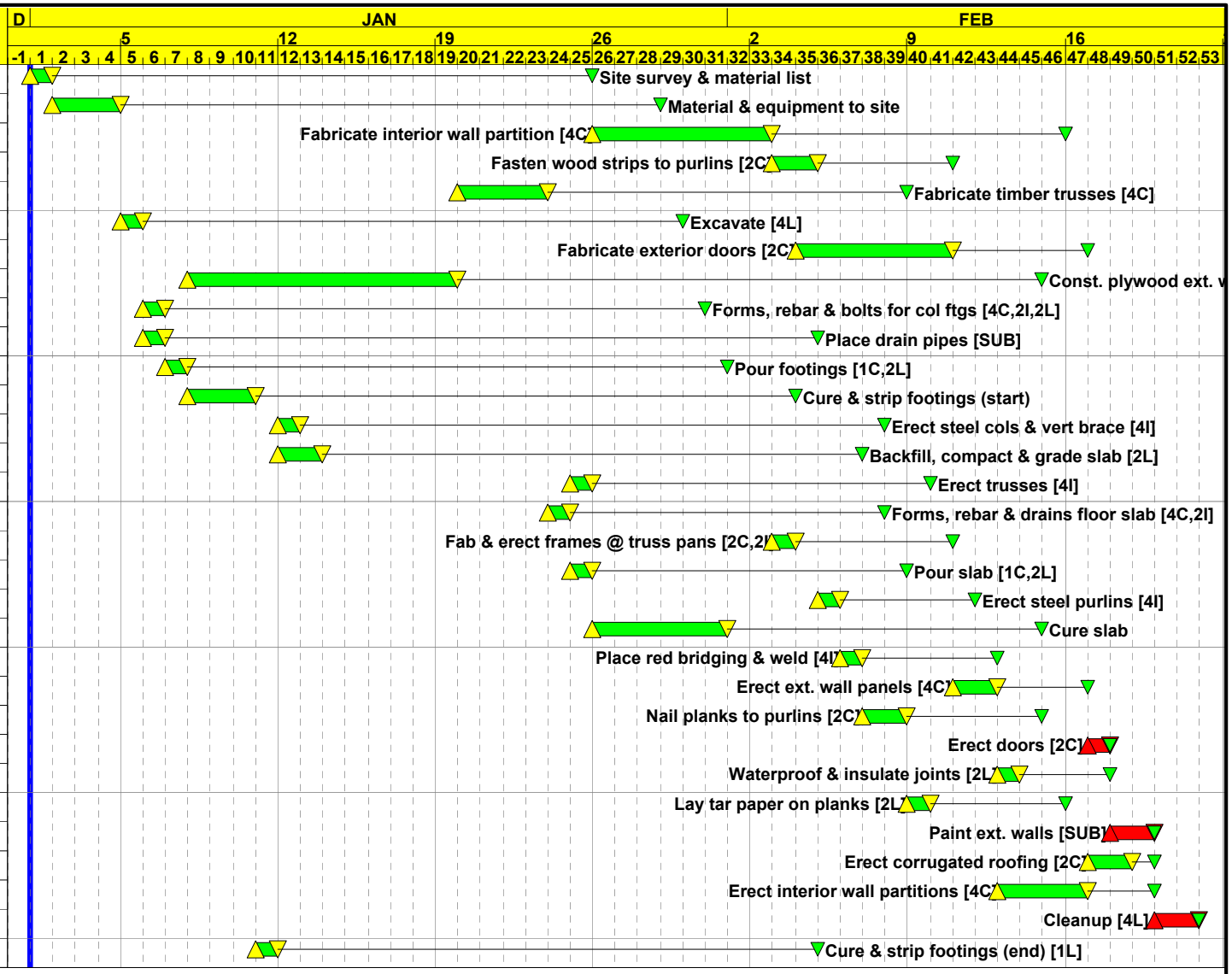
WARE Sheet 1 of 1

Warehouse Project (Before Change Order)
Leveled by P3, With Splits: T=28 days
Act5=6d(1W,2B,3W); Act8=5d(1W,2B,2W)

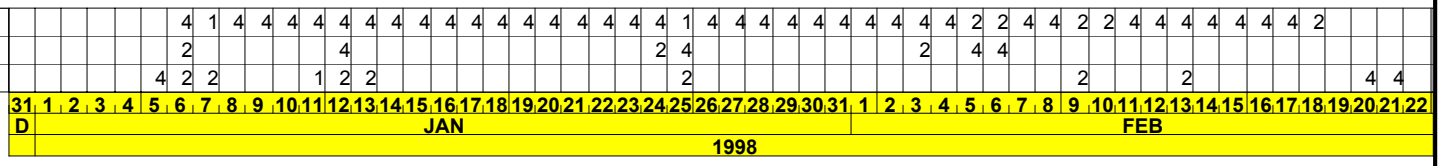
P3 splits Act 8 differently from Fondahl's paper:
P3 : 3 days = 1day + 2 days
Fondahl: 3 days = 2 days + 1 day

Thus, the TF for Act. 4 to 8B shown in Fondahl's paper are different from those in P3: "Alternate Optimum"

ID	Act	T	TF	FF
1	Site survey & material list	1	24	0
2	Material & equipment to site	3	24	0
3	Fabricate interior wall partition [4C]	8	13	10
4	Fasten wood strips to purlins [2C]	2	6	0
5	Fabricate timber trusses [4C]	4	16	1
6	Excavate [4L]	1	24	0
7	Fabricate exterior doors [2C]	7	6	6
8	Const. plywood ext. wall panel [4C]	12	26	22
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	24	0
10	Place drain pipes [SUB]	1	29	5
11	Pour footings [1C,2L]	1	24	0
12	Cure & strip footings (start)	3	24	0
13	Erect steel cols & vert brace [4I]	1	26	12
14	Backfill, compact & grade slab [2L]	2	24	10
15	Erect trusses [4I]	1	15	8
16	Forms, rebar & drains floor slab [4C,2I]	1	14	0
17	Fab & erect frames @ truss pans [2C,2I]	1	7	1
18	Pour slab [1C,2L]	1	14	0
19	Erect steel purlins [4I]	1	6	0
20	Cure slab	6	14	10
21	Place red bridging & weld [4I]	1	6	0
22	Erect ext. wall panels [4C]	2	4	0
23	Nail planks to purlins [2C]	2	6	0
24	Erect doors [2C]	1	0	0
25	Waterproof & insulate joints [2L]	1	4	4
26	Lay tar paper on planks [2L]	1	6	3
27	Paint ext. walls [SUB]	2	0	0
28	Erect corrugated roofing [2C]	2	1	1
29	Erect interior wall partitions [4C]	4	3	3
30	Cleanup [4L]	2	0	0
12B	Cure & strip footings (end) [1L]	1	24	0



Row	Group Name
1	Carpenters
2	Ironworkers
3	Laborers



Start Date 01JAN98
Finish Date 21FEB98
Data Date 01JAN98
Run Date 19JUN03 16:11

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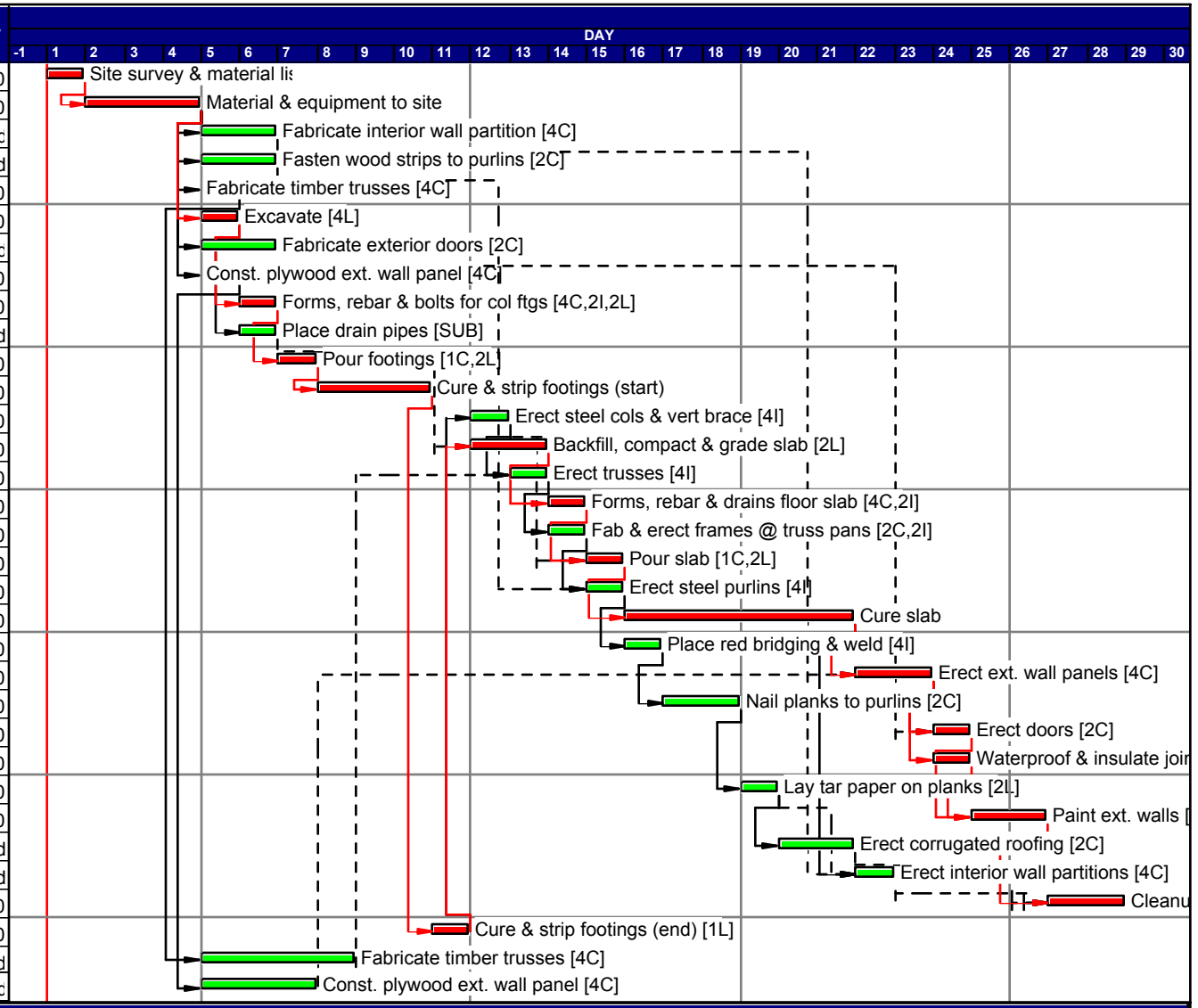
Early Bar
Float Bar
Progress Bar
Critical Activity

WARE Sheet 1 of 1

Warehouse Project (After Change Order)
Levelled by P3, No Splits: T=52d
T3=2+6=8, T7=2+5=7, T8=3+9=12, T29=1+3=4

Project Duration = 52 days
Same as found by Fondahl using P3 and no splits

ID	Description	T	Pred	TF	FF
1	Site survey & material list	1		0	0
2	Material & equipment to site	3	1	0	0
3	Fabricate interior wall partition [4C]	2	2	19d	15c
4	Fasten wood strips to purlins [2C]	2	2	13d	8d
5	Fabricate timber trusses [4C]	0	2	9d	0
6	Excavate [4L]	1	2	0	0
7	Fabricate exterior doors [2C]	2	2	17d	17c
8	Const. plywood ext. wall panel [4C]	0	2	14d	0
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	6	0	0
10	Place drain pipes [SUB]	1	6	5d	5d
11	Pour footings [1C,2L]	1	9	0	0
12	Cure & strip footings (start)	3	11	0	0
13	Erect steel cols & vert brace [4I]	1	12B	2d	0
14	Backfill, compact & grade slab [2L]	2	10, 12B	0	0
15	Erect trusses [4I]	1	13, 5B	5d	0
16	Forms, rebar & drains floor slab [4C,2I]	1	14	0	0
17	Fab & erect frames @ truss pans [2C,2I]	1	15	5d	0
18	Pour slab [1C,2L]	1	13, 16	0	0
19	Erect steel purlins [4I]	1	17, 4	5d	0
20	Cure slab	6	18	0	0
21	Place red bridging & weld [4I]	1	19	5d	0
22	Erect ext. wall panels [4C]	2	20, 8B	0	0
23	Nail planks to purlins [2C]	2	21	5d	0
24	Erect doors [2C]	1	22, 7	0	0
25	Waterproof & insulate joints [2L]	1	22	0	0
26	Lay tar paper on planks [2L]	1	23	5d	0
27	Paint ext. walls [SUB]	2	24, 25	0	0
28	Erect corrugated roofing [2C]	2	26	5d	5d
29	Erect interior wall partitions [4C]	1	20, 26, 3	4d	4d
30	Cleanup [4L]	2	27, 28, 29	0	0
12E	Cure & strip footings (end) [1L]	1	12	0	0
5B	Fabricate timber trusses [4C	4	5	9d	4d
8B	Const. plywood ext. wall panel [4C]	3	8	14d	14c



ID	Description	Units	Display: Quantity
C	Carpenters	CA	16 20 9 4 6 1 2 2 2 2 8 4 2
I	Ironworkers	IW	2 4 4 4 4 4
L	Laborers	LB	4 2 2 1 2 2 2 2 4 4

-1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
DAY

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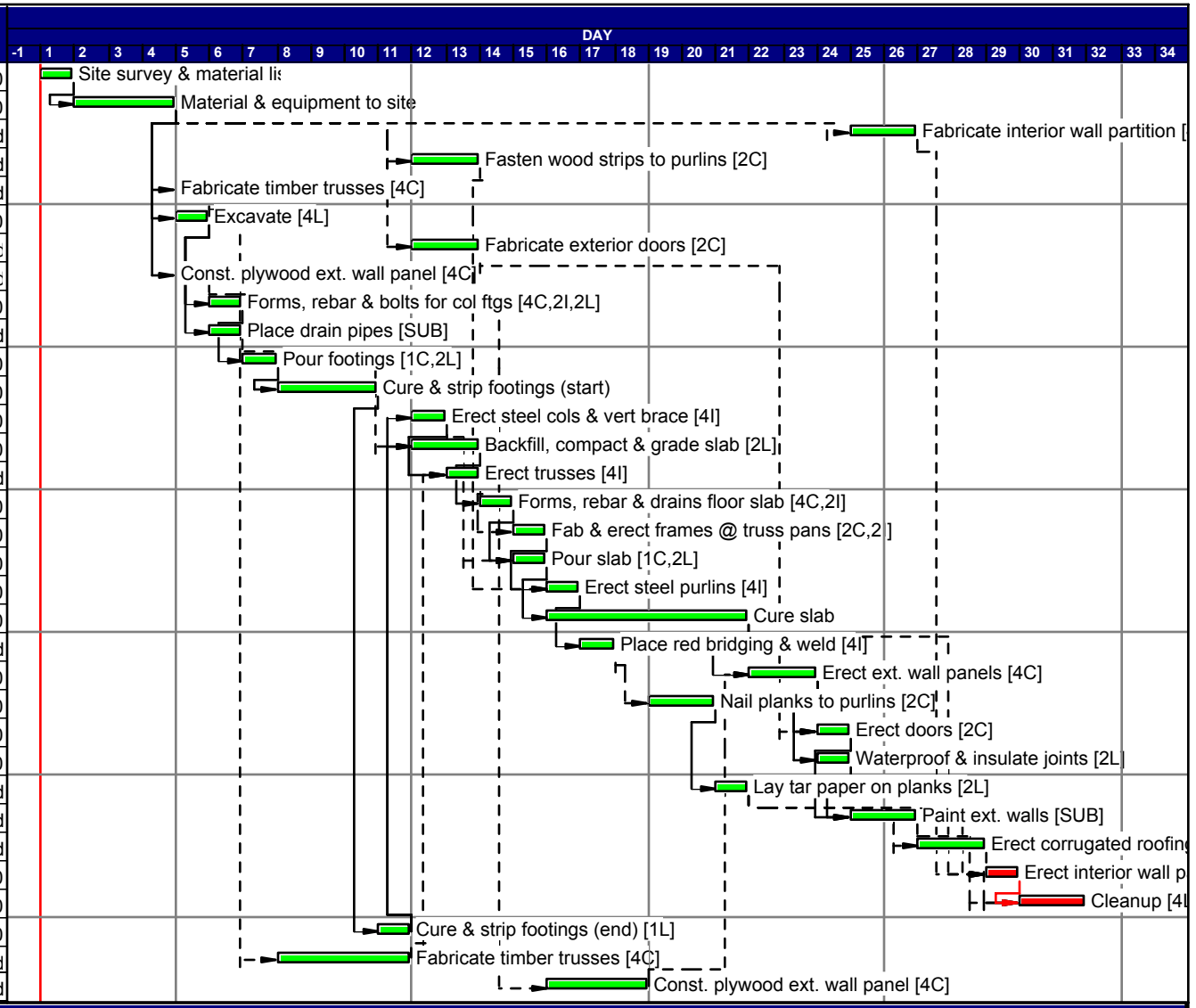
Warehouse Project (Before Change Order)
SureTrak, NoLeveling: T = 28 d
Avail. Res.: 4C,4I, 4L
Notice: Needed C >> 4

C.O. changes Act. Durations (dT):
T3 = 2 + 6 = 8 (dT=6 < FF=15)
T7 = 2 + 5 = 7 (dT=5 < FF=17)
T8 = 3 + 9 = 12 (dT=9 < FF=14)
T29 = 1 + 3 = 4 (dT=3 < FF=4)

Early bar
Progress bar
Critical bar
Summary bar
Start milestone point
Finish milestone poin

ID	Description	T	Pred	TF	FF
1	Site survey & material list	1		3d	0
2	Material & equipment to site	3	1	3d	0
3	Fabricate interior wall partition [4C]	2	2	2d	2d
4	Fasten wood strips to purlins [2C]	2	2	9d	2d
5	Fabricate timber trusses [4C]	0	2	12d	3d
6	Excavate [4L]	1	2	3d	0
7	Fabricate exterior doors [2C]	2	2	13d	10c
8	Const. plywood ext. wall panel [4C]	0	2	17d	11c
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	6	3d	0
10	Place drain pipes [SUB]	1	6	8d	5d
11	Pour footings [1C,2L]	1	9	3d	0
12	Cure & strip footings (start)	3	11	3d	0
13	Erect steel cols & vert brace [4I]	1	12B	5d	0
14	Backfill, compact & grade slab [2L]	2	10, 12B	3d	0
15	Erect trusses [4I]	1	13, 5B	8d	1d
16	Forms, rebar & drains floor slab [4C,2I]	1	14	3d	0
17	Fab & erect frames @ truss pans [2C,2I]	1	15	7d	0
18	Pour slab [1C,2L]	1	13, 16	3d	0
19	Erect steel purlins [4I]	1	17, 4	7d	0
20	Cure slab	6	18	3d	0
21	Place red bridging & weld [4I]	1	19	7d	1d
22	Erect ext. wall panels [4C]	2	20, 8B	3d	0
23	Nail planks to purlins [2C]	2	21	6d	0
24	Erect doors [2C]	1	22, 7	3d	0
25	Waterproof & insulate joints [2L]	1	22	3d	0
26	Lay tar paper on planks [2L]	1	23	6d	5d
27	Paint ext. walls [SUB]	2	24, 25	3d	3d
28	Erect corrugated roofing [2C]	2	26	1d	1d
29	Erect interior wall partitions [4C]	1	20, 26, 3	0	0
30	Cleanup [4L]	2	27, 28, 29	0	0
12E	Cure & strip footings (end) [1L]	1	12	3d	0
5B	Fabricate timber trusses [4C	4	5	9d	1d
8B	Const. plywood ext. wall panel [4C]	3	8	6d	3d



ID	Description	Units	Total	Display: Quantity
C	Carpenters	CA	78	4 1 4 4 4 4 4 4 4 3 4 4 4 2 2 4 4 2 4 4 2 2 4
I	Ironworkers	IW	22	2 4 4 2 2 4 4
L	Laborers	LB	27	4 2 2 1 2 2 2 2 2 4 4
Total				0 0 0 0 0 4 8 3 4 4 4 5 * * 6 7 8 8 4 2 2 2 4 4 4 4 4 2 2 4 4 4 0 0 0

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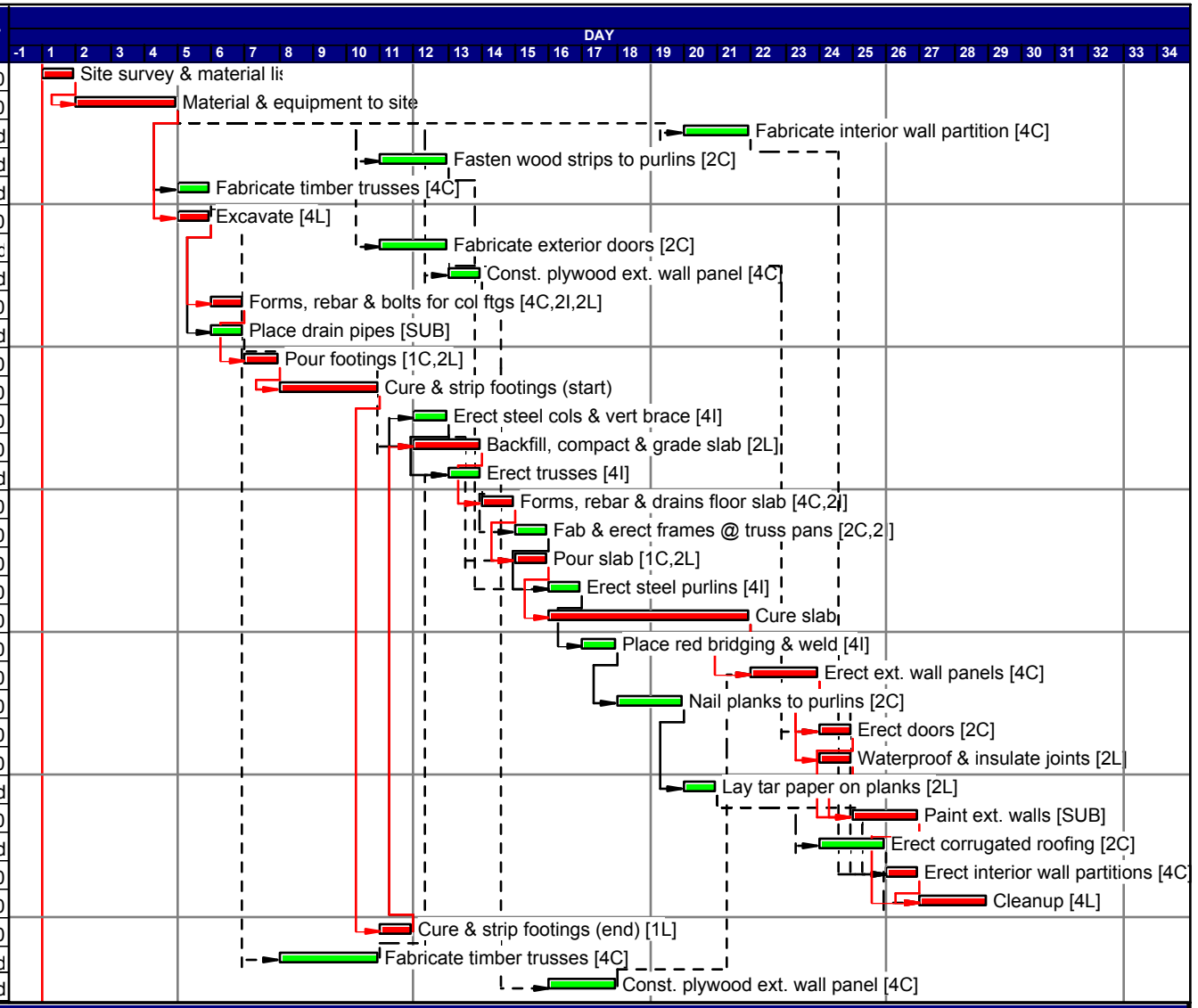
Warehouse Project (Before Change Order)
Levelled by SureTrak, No Splits: T = 31 days
(No Splits: T5=0, T5B=4, T8 = 0, T8B= 3)

Same as P3 and Fondahl without splitting

Early bar
Progress bar
Critical bar
Summary bar
Start milestone point
Finish milestone poin

ID	Description	T	Pred	TF	FF
1	Site survey & material list	1		0	0
2	Material & equipment to site	3	1	0	0
3	Fabricate interior wall partition [4C]	2	2	4d	4d
4	Fasten wood strips to purlins [2C]	2	2	7d	3d
5	Fabricate timber trusses [4C]	1	2	9d	2d
6	Excavate [4L]	1	2	0	0
7	Fabricate exterior doors [2C]	2	2	11d	11d
8	Const. plywood ext. wall panel [4C]	1	2	6d	2d
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	6	0	0
10	Place drain pipes [SUB]	1	6	5d	5d
11	Pour footings [1C,2L]	1	9	0	0
12	Cure & strip footings (start)	3	11	0	0
13	Erect steel cols & vert brace [4I]	1	12B	2d	0
14	Backfill, compact & grade slab [2L]	2	10, 12B	0	0
15	Erect trusses [4I]	1	13, 5B	5d	1d
16	Forms, rebar & drains floor slab [4C,2I]	1	14	0	0
17	Fab & erect frames @ truss pans [2C,2I]	1	15	4d	0
18	Pour slab [1C,2L]	1	13, 16	0	0
19	Erect steel purlins [4I]	1	17, 4	4d	0
20	Cure slab	6	18	0	0
21	Place red bridging & weld [4I]	1	19	4d	0
22	Erect ext. wall panels [4C]	2	20, 8B	0	0
23	Nail planks to purlins [2C]	2	21	4d	0
24	Erect doors [2C]	1	22, 7	0	0
25	Waterproof & insulate joints [2L]	1	22	0	0
26	Lay tar paper on planks [2L]	1	23	4d	3d
27	Paint ext. walls [SUB]	2	24, 25	0	0
28	Erect corrugated roofing [2C]	2	26	1d	1d
29	Erect interior wall partitions [4C]	1	20, 26, 3	0	0
30	Cleanup [4L]	2	27, 28, 29	0	0
12E	Cure & strip footings (end) [1L]	1	12	0	0
5B	Fabricate timber trusses [4C	3	5	7d	2d
8B	Const. plywood ext. wall panel [4C]	2	8	4d	4d



ID	Description	Units	Display: Quantity
C	Carpenters	CA	4 4 1 4 4 4 4 4 4 4 3 4 4 2 2 4 4 4 4 4 2 4
I	Ironworkers	IW	2 4 4 2 2 4 4
L	Laborers	LB	4 2 2 1 2 2 2 2 4 4

-1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
DAY

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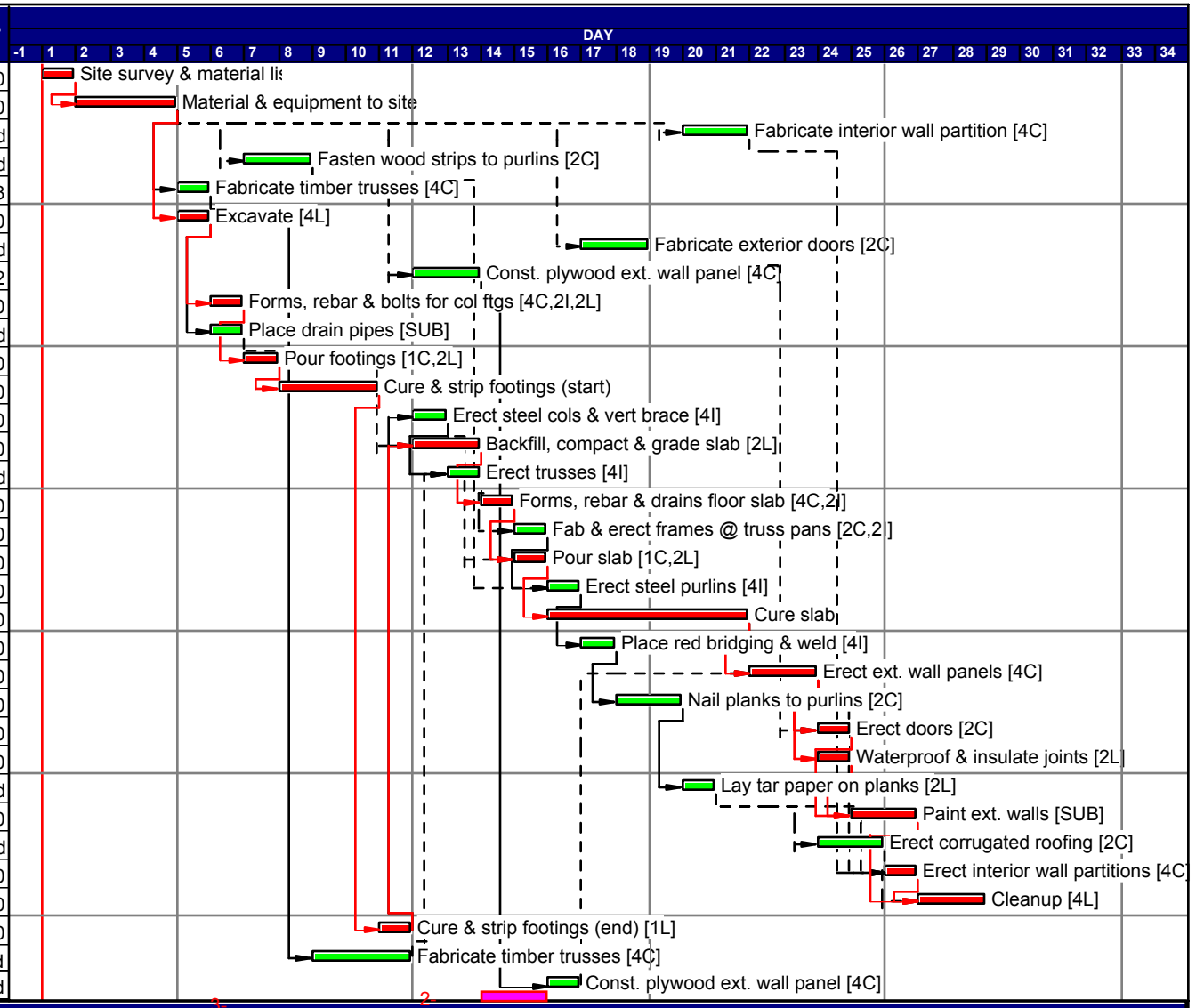
Warehouse Project (Before C.O.)
Levelled by SureTrak with P3 Splits for Act 8: T=28d
T5 = 1 + 3 = 4d, T8 = 1 + 2 = 3d

P3 splits Act 8 differently from Fondahl's paper:
P3 : T8 = 1 + 2 = 3 days
Fondahl: T8 = 2 + 1 = 3 days
Hence, TF are different: "Alternate Optimum"

Early bar
Progress bar
Critical bar
Summary bar
Start milestone point
Finish milestone poin

There are only 4 non-critical activities.

ID	Description	T	Pred	TF	FF
1	Site survey & material list	1		0	0
2	Material & equipment to site	3	1	0	0
3	Fabricate interior wall partition [4C]	2	2	4d	4d
4	Fasten wood strips to purlins [2C]	2	2	11d	7d
5	Fabricate timber trusses [4C]	1	2	9d	3
6	Excavate [4L]	1	2	0	0
7	Fabricate exterior doors [2C]	2	2	1 5d	5d
8	Const. plywood ext. wall panel [4C]	2	2	7d	2
9	Forms, rebar & bolts for col ftgs [4C,2I,2L]	1	6	0	0
10	Place drain pipes [SUB]	1	6	5d	5d
11	Pour footings [1C,2L]	1	9	0	0
12	Cure & strip footings (start)	3	11	0	0
13	Erect steel cols & vert brace [4I]	1	12B	2d	0
14	Backfill, compact & grade slab [2L]	2	10, 12B	0	0
15	Erect trusses [4I]	1	13, 5A	5d	1d
16	Forms, rebar & drains floor slab [4C,2I]	1	14	0	0
17	Fab & erect frames @ truss pans [2C,2I]	1	15	4d	0
18	Pour slab [1C,2L]	1	13, 16	0	0
19	Erect steel purlins [4I]	1	17, 4	4d	0
20	Cure slab	6	18	0	0
21	Place red bridging & weld [4I]	1	19	4d	0
22	Erect ext. wall panels [4C]	2	20, 8B	0	0
23	Nail planks to purlins [2C]	2	21	4d	0
24	Erect doors [2C]	1	22, 7	0	0
25	Waterproof & insulate joints [2L]	1	22	0	0
26	Lay tar paper on planks [2L]	1	23	3 4d	3d
27	Paint ext. walls [SUB]	2	24, 25	0	0
28	Erect corrugated roofing [2C]	2	26	1d	1d
29	Erect interior wall partitions [4C]	1	20, 26, 3	0	0
30	Cleanup [4L]	2	27, 28, 29	0	0
12E	Cure & strip footings (end) [1L]	1	12	0	0
5A	Fabricate timber trusses [4C	3	5	6d	1d
8B	Const. plywood ext. wall panel [4C]	1	8	1 5d	5d



ID	Description	Units	Display: Quantity
C	Carpenters	CA	4 4 3 2 4 4 4 4 4 4 3 4 2 4 2 4 4 4 4 2 4
I	Ironworkers	IW	2 4 4 2 2 4 4
L	Laborers	LB	4 2 2 1 2 2 2 2 4 4

Resource-

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Warehouse Project (Before C.O.)
Levelled by SureTrak with Fondahl's Splits for Act 8: T=28d
T5 = 1+3 = 4d, T8 = 2+1 = 3d

P3 : T8 = 1 + 2 = 3 days
Fondahl: T8 = 2 + 1 = 3 days
TF column = Column (5) in Table 1 of Fondahl's paper

Early bar
Progress bar
Critical bar
Summary bar
Start milestone point
Finish milestone poin