Applying *Critical Chain* to Improve the Management of Uncertainty in Projects

by

Stephen Carl Cook

B.S. Electrical Engineering, United States Naval Academy, 1989

Submitted to the Sloan School of Management and the
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Abstract

In an ever-intensifying global competitive market, the management of projects, particularly product development efforts, increasingly is one of the few areas that can produce a sustained competitive advantage. Firms that can bring products to market faster can extract higher initial margins, can be more responsive to their customers, and will have products with longer sales lives. Critical Chain is a new methodology that applies Eli Goldratt's Theory of Constraints to project management in order complete projects faster and with greater predictability while simultaneously making more efficient use of resources. The Critical Chain method accomplishes this by building project networks with average task durations, aggregating buffer at the end of projects where it can absorb unplanned iterations and other delays, and de-conflicting resources, both within and across projects. This new project management methodology was researched by spending seven months on site with ITT Night Vision and applying the method to two product development projects. In addition, benchmarking studies of previous product development efforts at the same site and of another lead user of the tool were conducted to provide both qualitative and quantitative comparison data. Critical Chain appears to minimize schedule risk while simultaneously minimizing project duration, and has the potential to improve both communication and employee morale.

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I dedicate this thesis to my children, Alexis and Christian, who brighten every moment of each day.

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1.1 Background

> *"The majority of all development projects fail to meet their time and cost targets, with the overrun typically between 40 and 200 percent."* [Roberts, 1995]

Cost and schedule overruns on public projects are infamous. Project managers are judged on cost, schedule, and performance. Most will admit they trade these off against each other but can rarely attain all three at once. Of all the skills which can give a company a competitive advantage in today's markets, project management is probably the most important. Yet, how many companies tout themselves as being "World Class in Project Management"? How many companies can routinely finish projects on time, within budget, and without cutting scope? Here are examples of typical project performance from three different industries:

Information technologies:

> "During the past 6 years, agencies have obligated over $145 billion building up and maintaining their information technology infrastructure. The benefits from this vast expenditure, however, have frequently been disappointing. GAO reports and congressional hearings have chronicled numerous system development efforts that suffered from multimillion dollar cost overruns, schedule slippages measured in years, and dismal mission-related results."[U.S. Government Accounting Office, 1997]

U.S. Federal Aviation Administration:

> "Since the 1980's, FAA's modernization efforts experienced substantial cost overruns and lengthy schedule delays. The cornerstone project in FAA's plan was the Advanced Automation System (AAS), a major program to replace all the hardware and software in FAA towers, terminals, and en route facilities. AAS was initiated in the early 1980's. By the early 1990's the estimated cost for AAS increased from the original $2.5 billion estimated in 1983 to $7.6 billion. The program was approximately 8 years behind the original schedule." [Office of the Inspector General, 1997]

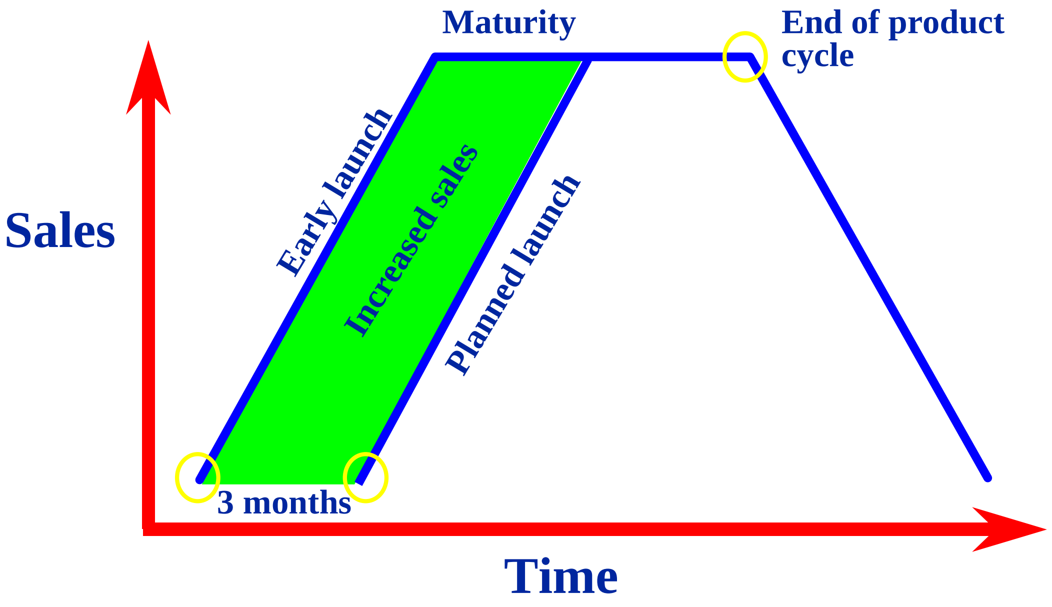
This is not a new problem caused by the complexity of technology. For example, the U.S.S. Constitution design started on June 28, 1794. Construction began in late 1795. The cost was originally estimated to be about $100,000. The Constitution finally launched in October 1797, double the originally estimated time to delivery, with the total cost at $302,000.

1.2 Product Development Cycles

Huthwaite states it well, “Contrary to what you read in the industrial press, most companies still have yet to master the ability to consistently bring products to market at the right time, at the right price, and with the right customer needs filled.” [Huthwaite, 1994]

As product life cycles shorten, the need to slash time to market becomes ever more critical. There is a general belief that product development will be the competitive battleground that defines world-class manufacturers for the next decade. As the MIT Center for Innovation in Product Development stated in its proposal to the National Science Foundation, “The stakes are extremely high, not only for the companies and their partners, but for the nation as a whole. Many product development projects fail, often resulting in huge losses.” [Seering et al, 1996] Assuming the product development team does not sacrifice quality in the rush to meet time-to-market goals, shorter product development cycles give a company four distinct advantages. First, the product’s sales life is extended. For each day cut from a product’s development cycle, a day is added to its sales life. Second, shorter development cycles free up valuable engineering time to work on other product introductions. Third, the first company to the market has temporary monopoly power and can extract higher margins because of this. Lastly, by definition if a product is first to market, it initially gains 100% of the market share. It is easier for a product to retain market share than it is for later competitors to win it. Clark and Wheelright point out, “In a competitive market that is global, intense, and dynamic, the development of new products and processes increasingly is a focal point of competition. Firms that get to market faster and more efficiently with products that are well matched to the needs and expectations of target customers create significant competitive leverage.” [Clark and Wheelright, 1993]

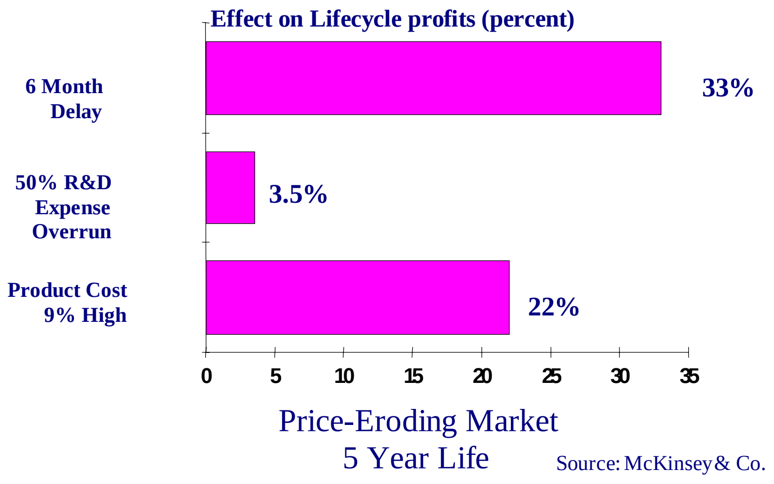
Speed to market also enables a company to be more responsive to its customers and ensures customer or market research is more up to date. The earlier a product is introduced, the more likely it is to gain market share and hold onto it. This is especially true in newer markets where standards are being set. [Huthwaite, 1994] A difference of 4-5 months in the timing of market introduction will have important strategic and financial implications in a market like automobiles where product introductions are associated with gains in market share. For example, in the case of a car that sells for $10,000, previous research indicates that each day of delay in market introduction costs an automobile firm over $1 million in lost profits. [Clark, 1989] One conservative model of the additional revenue, which can be earned by a three-month earlier release (or lost from a three-month late release), is shown in Figure 1.



A three-month savings in development time translates into three additional months of mature sales

Figure 1: Effect of Three Month Early Product Release

As can be seen in Figure 2, given the assumptions Reinertsen makes, his study showed that time to market was the most critical factor on lifecycle profits. This thesis describes the implementation of a new approach to project management, Critical Chain (CC) [Goldratt, 1997]. This tool has been touted to significantly reduce the chances of project overruns. The goal of this research was to apply and critique Goldratt's Critical Chain.



Source: McKinsey & Co.

Figure 2: Time to Market is the Most Critical [Reinertsen, 1983]

1.3 “Typical” Project Management

“The system you currently have is designed to give you the results you are getting now.” J. Covington

The following is a typical scenario observed by the author during experience before ITT:

> The schedules were usually put together during the proposal phase of the project. Because there was a good chance the project would not be undertaken, there was little motivation to put a lot of time into putting together a detailed, realistic schedule. The schedules that were more detailed emphasized the project logistics, such as travel, reports and reviews, but little analysis was directed at planning how and who would accomplish the bulk of the real work. Furthermore, this schedule was usually put together by the proposal team, which might or might not be members of the eventual project team. Managers usually intended to put together a more detailed schedule with the project team if the contract was awarded. In reality, this seldom took place because once the contract was awarded, the team already felt time pressure and “couldn’t afford” to invest time into the schedule. This led to schedules with not much buy-in from the project team participants and not enough detail to assist managers with decision making.

A schedule with sufficient detail can be used as a predictive model for the project. A good model can help managers forecast project performance and facilitate quality decision making. It can also help to shorten project feedback loops and thus, accelerate team learning. An inaccurate or superficial schedule will only serve to lead management and the team into a false sense of security.

Another trait prevalent in project management today is that resources (the people and machinery necessary to complete a task) are given task due dates and not task durations. This gives them little motivation to turn over work early, and leads to the “student syndrome,” which will be discussed in the next section. Furthermore, team members tend to be evaluated on whether they finish their tasks by the due date as if this is a binary piece of information. If they hand work in on time, the primary metric is the quality of their work. The incentive this gives resources is that if they finish a task ahead of schedule, they should continue to optimize it until the due date and then hand it over. Puneet Saxena, project manager for Harris Semiconductor, stated in a taped interview, “Traditional project management does not deal effectively with accumulating positive variations in task completion times." [Saxena, 1997] Also, there is no sense of a growing penalty to the project team once one has missed the due date.

Typical schedules do not have aggregated buffers or safety time built into them (they usually have unacknowledged safety time built into each task estimate). What commonly happens is that the middle of a schedule will slide to the right, while the finish date is held firm. This leads to a “bow wave” crashing over the heads of resources that were unfortunate enough to be listed at the end of the schedule. Inevitably, their task durations are compressed. This forces workers to either trade quality for time, or miss the assigned due date. Also, there is little attention paid to resource deconfliction. The schedule does not model that an essential resource will have more than one task to complete simultaneously. Some project managers do attempt to level the workload within scheduling software, such as Microsoft Project, but this feature is cumbersome and is unknowingly undone automatically if further changes are made to the schedule.

Due to the factors mentioned above and the fact that resources are evaluated on individual task completion success, employees are given the incentive to pad their estimates with individual safety. Newbold states, “In order to be competitive, task times are often factored down, sometimes arbitrarily.” [Newbold, 1997] This leads to schedules with near meaningless task estimates, which in turn leads to poor decision making.

A schedule’s Critical Path is the longest path through the network due to predecessor/successor constraints. Because of this, the Critical Path Methodology (CPM) states that a team must concentrate their efforts on the Critical Path in order to shorten the overall project. This is the most commonly used project management tool in industry. Thus, the author will use it to benchmark Critical Chain. Although CPM is well understood, local schedule optimization still occurs. The impression seems to be that if each resource performs his or her assigned tasks as quickly as possible, this will by definition lead to the optimal schedule performance. To this end, management attention can be on all tasks, with long meetings discussing how each task is progressing.

1.4 Summary of Critical Chain Methodology

1.4.1 The Theory of Critical Chain

Critical Chain is a book published in 1997 and written by Eliyahu Goldratt. Goldratt outlines how the Theory of Constraints (TOC) can be applied to projects to improve performance. Goldratt’s first book, *The Goal*, revolutionized manufacturing by describing how TOC could be applied to the factory floor. TOC is a common sense management philosophy that espouses that in order to improve the performance of any system, one must first find the constraint of the system and then concentrate effort on elevating the capacity of the constraint.

For simplicity’s sake, in typical project management such as CPM, task durations are treated as if they are deterministic, when in fact they are highly probabilistic. Project managers are attempting to simplify their jobs using methodologies that were designed before the advent of computers, unknowingly causing many undesirable effects. Software allows a project manager to easily deal with the inherent uncertainty in project management and allow a schedule to be dynamic. Treating task duration estimates as probabilities solves many of the problems projects are currently facing using prevalent methodologies.

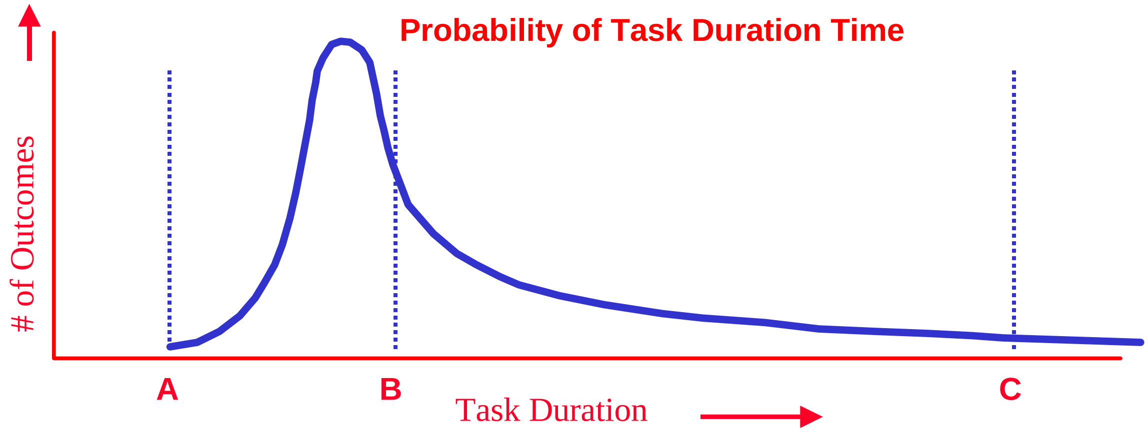


Figure 3: Distribution of Possible Task Duration Outcomes [Jacobs, 1997]

Goldratt contends that most schedules have safety time built into each task estimate. Figure 3 above shows a general distribution that represents the possible outcomes for most tasks. It is a normal distribution with a finite left tail because things can only go so well. A task will never be finished in zero or negative time. On the other hand, quite a lot can go amiss. This explains the long right tail. When a person is asked to estimate task duration, consciously or subconsciously he or she is picturing a graph like the one above which is built from historical data points. Time “A” is the “Pure Success” basis. It is not likely to repeat and, unless someone is very new to project management, will never be given as a task estimate. Time “C” is highly achievable, even with a major disaster. This is the time commonly used because this is what incentive systems have trained workers to give as estimates. Goldratt calls this the “95% time” because 95% of the time a resource will finish in less time than the given estimate (and look good in management’s eyes). Furthermore, if management has a practice of cutting all estimates across the board to squeeze a schedule into a given amount of time, this is even more incentive for team members to give “C” or even “C+” times. “Even though we were trying to offer our best estimates with as little safety built in, there were sufficient buffers built in there. This stems from the fact that in the back of our minds we’re allowing for resource contention or multi-tasking and also thinking ‘I’ll get to it in the end.’” [Saxena, 1997] Time “B” represents the duration estimate such that 50% of the outcomes are less than it, and 50% of the outcomes are greater. In other words, if a resource gives this duration as an estimate he or she has a 50/50 chance of finishing on time. This is the median task duration and the time estimate one attempts to build into a Critical Chain schedule. Theoretically, the average task duration should be used, but studies have shown that even when people are asked to estimate an average duration, they instead provide the median duration. [Kahneman, Slovic, and Tversky, 1982] Because of the long right tail, the median duration should be slightly less than the average duration, but this difference should not be significant for CC’s purposes.

A portion of the time saved by moving from “C” to “B” task estimates is then aggregated at the end of the schedule to act as an overall “shock absorber” for the entire project. This aggregated buffer is called the “Project Buffer.” Consolidated buffer is also placed at the juncture of all non-critical paths with the project’s critical path. These buffers are called “Feeder Buffers” and their purpose is to protect the critical path from the variability of non-critical path tasks.

One problem with leaving small amounts of buffer time in each task estimate, instead of aggregating it, is that the safety is often wasted at the beginning of the task period, not the end where it can do good. Goldratt outlines three ways in which safety, or buffer, is typically wasted. The first is called “Student Syndrome.”

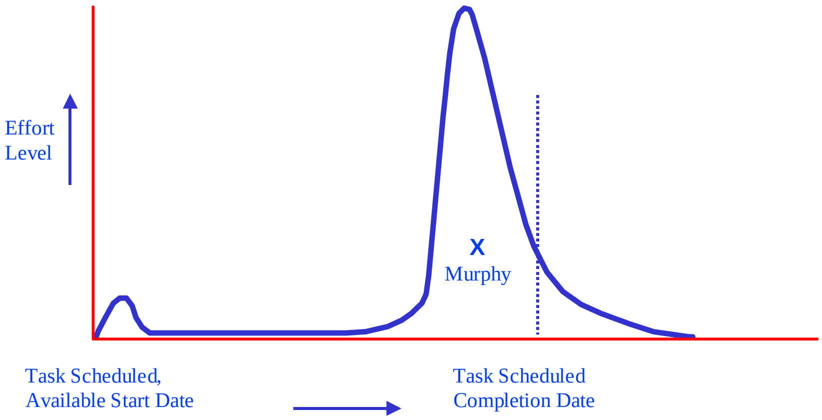


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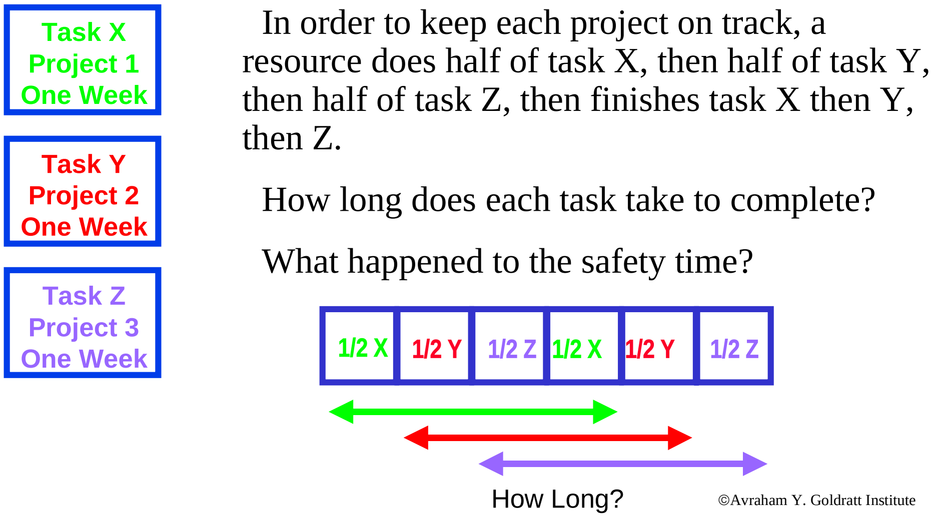
Figure 4: Student Syndrome

Goldratt contends that once a resource has negotiated a “C” time, they reevaluate the task and decide how long it will most likely take. Then they get caught up working on other projects with closer deadlines. When they have only the expected duration left until the deadline, they really ramp up the effort level. At that point, if they encounter an unexpected problem, the deadline is missed. Notice that if the resource would have started the work when it was assigned, they still could have easily met the deadline, even with the “Murphy.”

The next way in which safety is wasted is the multiplying effect of multi-tasking.



In order to keep each project on track, a resource does half of task X, then half of task Y, then half of task Z, then finishes task X then Y, then Z.

How long does each task take to complete?

What happened to the safety time?

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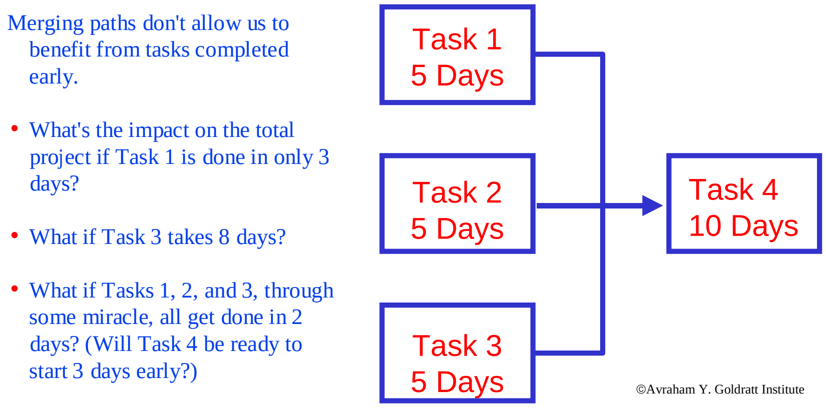
Figure 5: The Multiplying Effect of Multi-Tasking

If a resource has three tasks assigned in descending priority X, Y and Z, what often happens is that they will start task X and work on this unless the work is "reprioritized." Most project managers are given the incentives that drive them to be concerned only with optimizing their project. Furthermore, they have learned from experience that in project management "the squeaky wheel gets the grease." Thus, what will typically happen is that Y's project manager will go to the resource and ask what progress he or she has made on his task. Not wanting to disappoint Y's project manager, the resource will drop what he or she is doing on task X and start working on task Y. This same thing happens with task Z, leading to the workload shown in the Figure 5. What has happened is that each one-week task has taken at least two weeks to complete. This picture does not even show the set-up time required when switching between tasks. The net effect is that each task finishes later than it would have if our resource had worked on task X until it was complete, then task Y, and then task Z.

The last way in which safety is wasted has to do with the structure of most schedules. Because tasks can have multiple necessary predecessors, delays are passed on, while gains are not.



Merging paths don't allow us to benefit from tasks completed early.

- What's the impact on the total project if Task 1 is done in only 3 days?
- What if Task 3 takes 8 days?
- What if Tasks 1, 2, and 3, through some miracle, all get done in 2 days? (Will Task 4 be ready to start 3 days early?)

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Figure 6: Schedule Structure Allows Delays to be Passed on while Gains are Not

The diagram and captions of Figure 6 illustrate how the structure of a conventional schedule causes a lose-lose situation. A delay in any of the three predecessors will be passed on to the successor, while any gains will not be passed on. Even if all three predecessors finish early, because we build our schedules around due dates, most likely the successor resource will not be ready to start his or her task early.

1.4.2 Converting a Critical Path Schedule into a Critical Chain Schedule

This section uses a highly stylized PERT schedule with only two branches feeding into one final task. The simplicity of the schedule clarifies the logic of the transformation, which also scales up to schedules with complexity that is more realistic.

As can be seen in Figure 7, the letter in each block represents the resource (usually a person or group of people) necessary to complete the given task. Assume there is only one available resource for each given letter. The number in each block represents the estimated duration of the task in days.

The first step in the conversion is to attempt to pull the safety out of each duration estimate and get at the median times for each task ("B" times). In this example, this is shown as half of the initial "C" estimate. This is the rule of thumb that Goldratt recommends using.

The next step is to aggregate all of the safety at the end of the project where it can act as an overall buffer for the entire project. The date one would commit to a marketing campaign or to senior management would be at the end of this project buffer, not at the shown finish of task "E." Theoretically, this is the only date that remains fixed in a CC schedule. This project buffer becomes a necessary component of the schedule, and must not be considered "padding."

The safety from the shorter branch has also been consolidated into the feeding buffer. This serves to immunize the critical path against negative variations of the feeding path. In effect you are giving the feeding path its own safety so that if it runs into delays, unless the entire feeder buffer is "eaten," the delays will not be passed on to the rest of the schedule.

In general with CC, one starts tasks as *late* as possible, which is a departure from how Microsoft Project will automatically schedule a project (it will start all tasks as *early* as possible). Because work is started later and generally worked on until it is complete, this helps reduce work in progress (WIP). From a management point of view this is beneficial because WIP is costly and can serve to bog workers down. This can also be a difficult paradigm shift for a team to make. Feeder paths are started a defined amount (feeder buffer) earlier than necessary as a risk reduction. As can be seen, at this point both versions of the schedule are 64 days long.

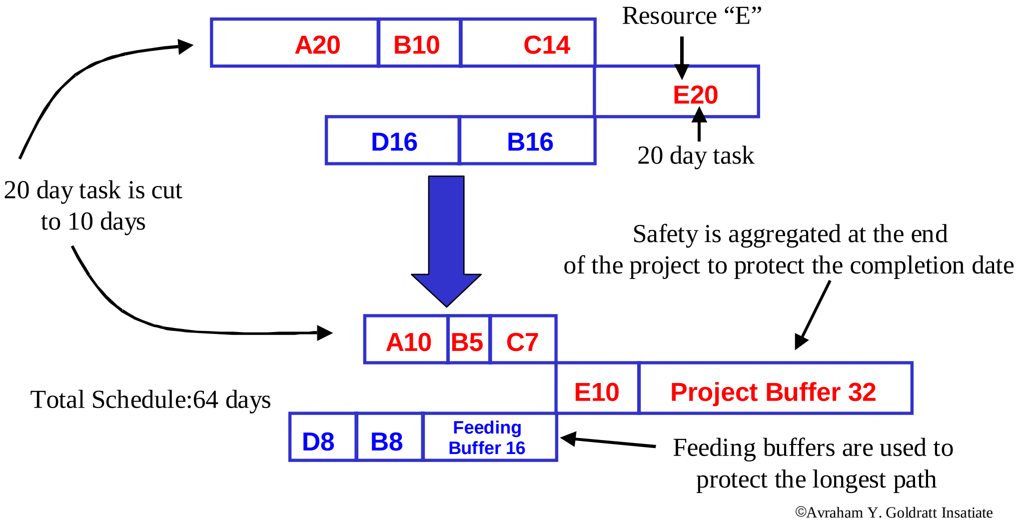
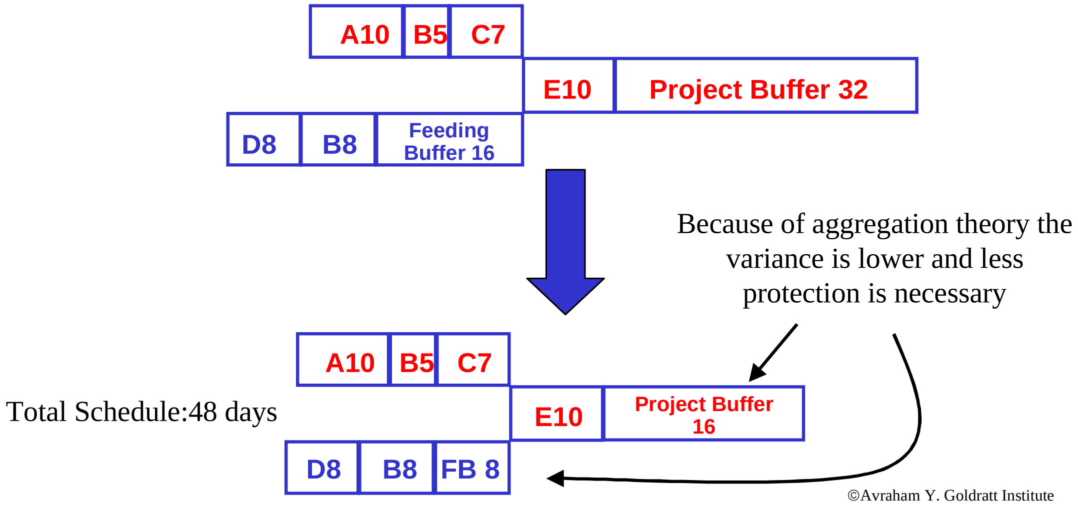


Figure 7: Aggregate the Buffer at the End of the Schedule

The next step is considered one of the most powerful aspects of Critical Chain. Because of random number aggregation theory, the overall variance of the critical chain will be much less than the addition of all the individual variances for each CC task. In other words, the amount of protection necessary when you aggregate all of the tasks is much less than if you added the protection originally built into each estimate. In the example below, the buffer is cut in half, leaving a buffer length of one half the length of the CC (Goldratt recommendation). The same applies to feeding paths, so that a feeding buffer is optimally one half the length of the feeding branch against which it is protecting.



Because of aggregation theory the variance is lower and less protection is necessary

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Figure 8: Aggregation Theory Allows Buffers to be Cut

The schedule has been cut from 64 days to a total of 48 days, but Goldratt would contend this schedule has a much better chance of finishing on time than the original longer schedule. This is because the buffer has been concentrated at the end of the schedule where it can do good, allowing individual task early and late completions along the CC to counteract each other.

Notice that there is still one problem. Resource “B” is scheduled to perform two tasks simultaneously. Standard Microsoft Project and CPM will allow this, although most people recognize it leads to an unrealistic schedule. The next step in the conversion is to de-conflict resources. This is when the schedule is converted from a CPM schedule to a Critical Chain schedule.

As can be seen in Figure 9, the feeder branch is started earlier and becomes part of the longest chain of dependent tasks. The Critical Chain follows the dotted line from D8 to B8, then due to resource dependency up to B5. Notice that a feeder buffer is now placed in front of A10 to protect the CC against its uncertainty. Also, notice that the schedule has grown from 48 days to 57 days, but is much more realistic and predictable because resources are only counted upon to undertake one task at a time.

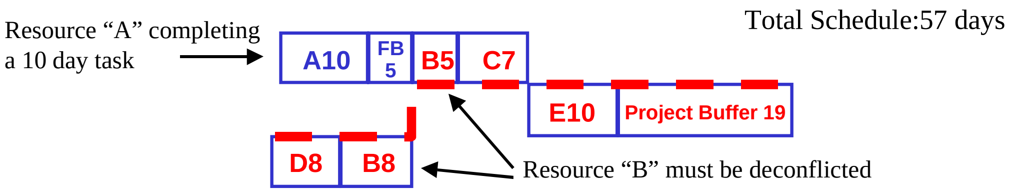

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Figure 9: The Critical Chain Takes into Account Resource Dependencies

In order to take advantage of early finishes and deal effectively with late finishes, a CC schedule must be very dynamic. Most project managers worry that logistically a dynamic schedule will become unmanageable, and thus opt for the "simpler" approach of trying to lock down the schedule by assigning due dates. While this might seem like a simpler approach, it leads to the undesirable effects mentioned in Section 1.3.1. The CC schedule does not become unmanageable because only the CC tasks must remain flexible. Unless there are major variances, feeder paths remain set.

The team makes a pact during the implementation of CC that all members will drop what they are doing to work on CC tasks and work non-stop on those tasks until they are complete. In this regard, a CC schedule is very similar to running a relay race. Team members wait to get the baton and then run as fast as they can until they pass the baton on to another teammate. The CC by definition defines the overall length of the project, thus it makes sense to concentrate all management attention on these tasks and "sprint" them as quickly as possible.

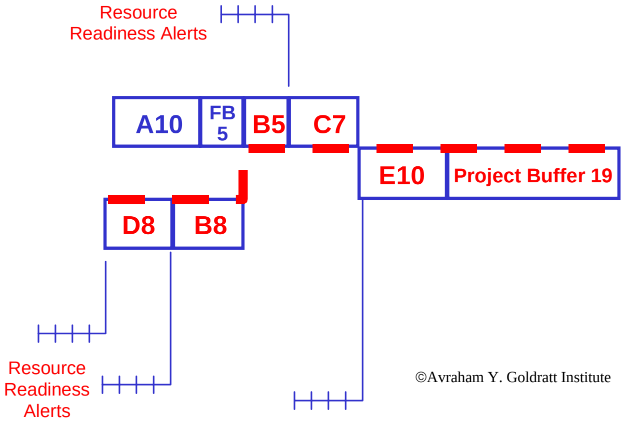

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Figure 9: Resource Readiness Alerts

Resource Readiness Alerts (RRA's, called Resource Buffers by Goldratt) allow a project team to remain aware of the CC. RRA's are a form of communication between the schedule keeper and the rest of the team. The schedule keeper will get task updates (Goldratt recommends daily) from all resources currently working on tasks as the schedule progresses. The resources merely need to report how many workdays remain until they estimate their task is complete. When a predecessor CC resource reports to have five days remaining (Goldratt recommended), the schedule keeper informs the successor they have approximately five days until they are on the CC. This is a dynamic countdown for the successor. If the predecessor reported two days later that he or she hit a glitch and still had five days remaining, this would be passed on to the successor. This allows CC resources to plan their work schedules and keep other project managers aware of their pending CC status.

The last major distinction of CC is the way in which the schedule is managed. Management controls the project by monitoring status of the buffers. This allows them to highlight the tasks that need immediate attention. A typical project will have numerous feeder buffers. The most consumed feeder buffer is protecting the feeder path with the highest probability of delaying the CC. Thus, management can focus attention on the feeder paths with the most depleted buffers. Of course, the CC tasks by definition are always considered crucial.

The buffers also help management to act proactively. Buffer management highlights potential problems much earlier than they would ordinarily be discovered using typical project management techniques.

The feeder and project buffers are broken into three zones similar to a traffic light indicator. The "green" zone is labeled "OK." If this portion is eaten into, management does nothing. This prevents micromanaging and over tweaking (this is very similar to SPC). The next zone of the buffer is labeled "Watch & Plan." In this "yellow" zone, the team would form a plan to put into action if further buffer is eaten. The last zone is labeled "Act." This is the "red" zone wherein management would expect its team to initiate the plans to increase the size of the buffer or at least prevent further erosion of it. Actions could be assigning more resources to certain tasks, working weekends, breaking finish-start constraints that might not have been necessary, etc. This is extremely powerful, especially because management can set the size of each zone based on past performance, inherent variability of the project, etc. Setting the size of each zone will in some regards define the degree of management involvement in the project.

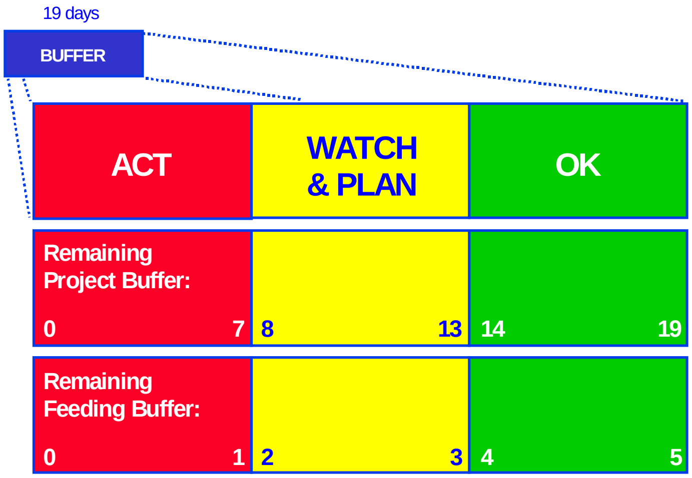

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Figure 9: Buffers Provide Focus and Early Warning

In Figure 9, the buffers are shown divided into three equal parts. Management should expect buffer to be eaten as the team advances through the project and runs into unexpected iterations or "Murphys." Thus, the buffers need to be divided relative to how much CC is left in the project. If a project has nine months left to complete with only two weeks of Project Buffer remaining, there is a very high probability the due date will be missed. On the other hand, if a project has two weeks left of CC, and the same two weeks of buffer, management will most likely not be very concerned. Management needs to monitor the buffers relative to how much CC or feeder branch remains, and the rate of buffer consumption.

1.4.3 Single Versus Multi-Project Implementation

There are two main categories of CC. The first is called single project implementation. The definition of single project implementation is that the projects are not predominantly utilizing the same resources. Within an organization, there can be multiple single CC projects. The second type of implementation is called multi-project implementation. Multi-project implementation indicates there are multiple simultaneous CC projects and many of the resources are shared across projects. It is more difficult to schedule resources across multiple projects because there is no clear decision metric when deciding which project to first allocate a constrained resource. Goldratt contends that CC and TOC can provide this global project metric.

Multi-projects require a higher level of implementation with much higher coordination requirements. At this level, an organization identifies which resource, on average, is the constraint across all the projects it undertakes. More strategically, an organization would identify which resource should be its constraint, and then have this resource or group of resources pace when new projects are undertaken by the entire organization (Goldratt calls this resource the “drumbeat”). As an example, if electrical engineers were in very short supply and thus demanding a premium, a design organization might want to staff itself such that electrical engineers are its constraint. All other resources would have, on average, more design capacity so that the electrical engineers were always the bottleneck. Thus, management could plan the design workload such that electrical engineers were always at full capacity. As the electrical engineers completed tasks, they would “pull” more design work into the company.

Pulling more design work into the company than the electrical engineers could handle would only serve to increase work in progress (WIP). This would slow the organization and do nothing to increase its throughput. Electrical engineers would act as the “drumbeat” for the design organization much as a manufacturing bottleneck acts as the “drumbeat” for a plant. In this way, applying Goldratt’s Theory of Constraints (TOC) to project management is very similar to applying TOC to a factory, albeit the variances or uncertainties are typically much greater in project management.

Goldratt contends that long term, most organizations should strive for the multi-project implementation. The benefits and drawbacks of starting with single project implementation are discussed in section 4.2. Since most of this research has been with single project implementation, the majority of this paper will discuss only single project implementation.

1.4.4 Fundamental Project Scheduling

The use of CC does nothing to preclude the use of other common sense project management tools. The more tasks can be decomposed into finer detail, the more this will allow the team to overlap tasks and shorten the CC. The team needs to be well versed in the difference between tasks that must be performed sequentially and those that can be performed in parallel. It is especially important to break the paradigms of tasks that have always been performed sequentially or performed by specific people (versus talents), that have no necessity to be done so. If anything, CC helps in applying these tools. As Puneet Saxena, a Project Manager from Harris semiconductor, stated “Many tasks that initially appear to be sequential can be done in parallel if resource contention is addressed up front.” [Saxena, 1997]

Once a team has preliminarily identified the CC for a project, they can take a much closer look at those tasks to identify opportunities for performing them in parallel. Many common techniques for shortening project duration are discussed by Smith and Reinertsen in their book *Developing Products in Half the Time*. [Smith and Reinertsen, 1991] The team will identify the constraint of the project (the CC) and then work to break that constraint. Once they have done so, they work to break the next constraint, until they get to the shortest practical schedule.

1.5 Critical Chain Summary

The goal of Critical Chain (CC) is to help projects finish on time, within budget, and without curtailing the objectives of the project (scope). The main points of CC are:

- It is a cultural change in how to manage projects and evaluate team members.
- Avoid multi-tasking, especially while on the Critical Chain.
- Protect against inherent uncertainty by aggregating all safety time at the end of the project rather than building it into individual task estimates.
- Concentrate on the constraint of the project: the longest chain of dependent tasks or resources (dependency can either be the standard CPM finish-start dependencies or resource dependencies).

2 Applications of Critical Chain at ITT Night Vision

2.1 The Projects

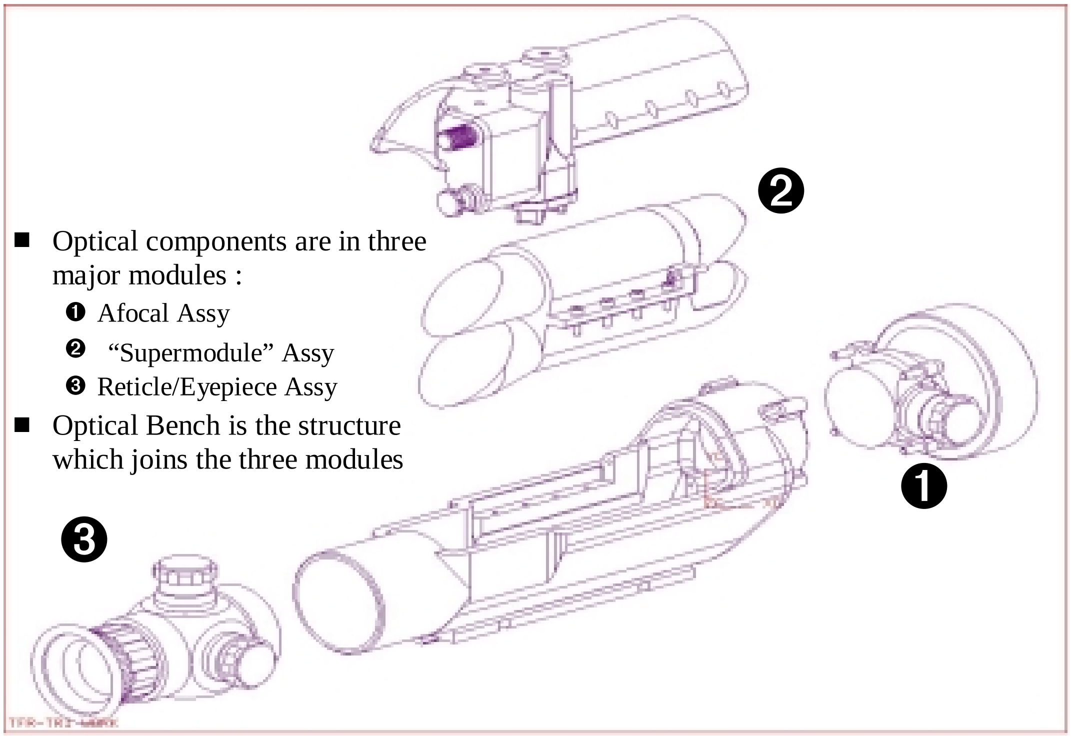
The author spent 7 months on site at ITT Night Vision in Roanoke, VA implementing Critical Chain as a member of two integrated product development (IPD) teams. ITT is a leader in the Night Vision industry, and very highly regarded by its primary customer, the United States military. Night vision is a technology which has historically been used predominantly by the military, but which recently has improved so dramatically both in performance and cost that it is being adapted for commercial uses. Night vision equipment is highly complex, but simply stated, it detects extremely low light emissions, converts these into weak electrical signals, boosts these signals 30,000 times, and then uses these boosted signals to excite a phosphorous-coated screen, which can be viewed by the user. For a more in-depth discussion of how night vision equipment works, see Appendix A. This technology has revolutionized warfighting and given the United States a significant advantage over its enemies.

2.1.1 Integrated Night/Day Observation/Fire Device (INOD)

The first CC pilot product development effort was a government contract that was awarded to ITT on June 24, 1997, shortly after the author's arrival on site. The team's preliminary mandate was to design and prototype six dual optical channel sniper scopes for the U.S. Special Forces within nine months. These scopes are to be attached to snipers' rifles to be used for both targeting and reconnaissance purposes. What will distinguish INOD scopes from what is in use today is that they will be effective in any light conditions. Today snipers carry both a day scope and a night attachment for long missions and must interchange the attachment at dusk and dawn. This is dangerous to the snipers, who hide themselves by remaining absolutely still. Furthermore, it adversely affects weapon accuracy (snipers usually "sight" a scope after installing it by shooting multiple rounds and adjusting the position of the crosshairs, obviously they can't do this during a mission). The INOD scopes will superimpose two images from separate, parallel, optical channels. One image will go through a night vision image intensifier (see Appendix A), the other will not. The overall government purchase is expected to be approximately 2000 units after the completion of a second nine-month test-analyze-fix cycle. Overall, the schedule is acknowledged as being extremely aggressive.

The IPD team consists of roughly ten design engineers/technicians from ITT R&D Engineering, and a representative each from manufacturing, purchasing, marketing, logistics and finance. The ITT team is also partnered with about seven engineers from Leica Optics in Switzerland who are responsible for the bulk of the optical design. Individuals from Knight's Armament in Vero Beach, FL are responsible for the weapon interface. The author's primary responsibilities were as assistant project manager and lead scheduler.

The team was to design two interchangeable Afocals (similar to the interchangeable lenses of a 35mm camera), a medium and a large. The large system must be able to identify a man-sized target at 1500 meters on a quarter moon night. The medium system must be able to identify a man-sized target at 1200 meters. Two AA batteries power the circuitry and must have a minimum full-on lifetime of 30 hours. Among the other stringent military specifications, the unit is to be watertight down to 66 feet and weigh under 4.5 lbs. (medium). Three of the six prototypes will be medium sized systems; the other three will be large sized.[1]



- Optical components are in three major modules :
  - ❶ Afocal Assy
  - ❷ “Supermodule” Assy
  - ❸ Reticle/Eyepiece Assy
- Optical Bench is the structure which joins the three modules

Figure 10: INOD Design

The product was described by the government optics expert as “the most complex optical design ever.” Light comes in through the Afocal (1) and then through an optical beam splitter (2). Some of the light travels through the upper optical path (night channel), which contains a night vision image intensifier (tube). The rest of the light travels through the lower optical path (day channel). At the back end of the super-module assembly (2), the light from both channels goes through a beam combiner and is focused on an aiming reticle (crosshairs) inside the reticle/eyepiece assembly (3), see Figure 11. Thus, the sniper should have a clear image of his target under the reticle day or night. The two images are required to be aligned within 1/120th of one degree after being subjected to 300 rifle shots that can have spikes up to 5000 times the force of gravity (5000 g’s). The reticle must be able to be precisely positioned in both azimuth (horizontally) and elevation (vertically) using the knobs (“clickers”) shown on the reticle/eyepiece assembly (3). These clickers are to mimic the present sniper scopes in feel and operation as closely as possible. The optical bench cover contains an electronics module. The top knob turns

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[1] Acquisition Program Baseline Agreement for the Improved Night/Day Fire Control/Observation Device (INOD)

the image intensifier on/off and controls image brightness. The electronics module also contains circuitry that can light up the crosshairs. The bottom knob is for reticle on/off and controls reticle brightness. The Afocal (lens) is focused using the knob shown on the right side of the assembly (1).

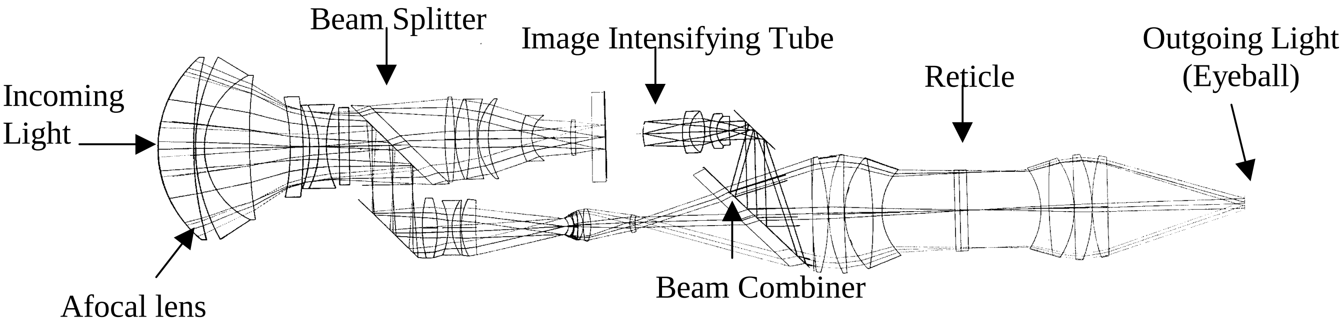


Figure 11: Light Trace of INOD Design

2.1.2 Low Cost Power Supply (LCPS)

The second project the author was assigned to was an internal research and development IPD team tasked to design a lower cost power supply. The highest cost item for any night vision product, with the exception of the image intensifier tube, is the power supply that powers the image intensifier tube. ITT Night Vision had been striving for a lower cost power supply for many years; ITT employees described this project as “the Holy Grail.”

A power supply is potted with each tube. Thus, in a two-tube system, such as a set of night vision goggles, there are two power supplies. The power supply takes 3V from two AA batteries and converts it into three separate voltages: V1 (typically –900V), V2 (adjustable from –600V through -1100V), and V3 (typically +4500V). The entire unit must be packaged in a very small cylinder with an inside diameter of .78”, an outside diameter of 1.3”, and a height of only .44”, for the smallest model.

The product also has to be able to withstand a grueling set of military specification tests such as temperature ranging from -32° through 52° C, 98% humidity for 240 hours, shock 75 g’s for 11 ms, and 9000 hours mean-time-between-failure. The power supply also has to be insensitive to Electro-magnetic interference (EMI) so that it will not transmit an Electro-magnetic signal during operation, which the enemy could detect. Lastly, since the customer highly values long battery life, it is also extremely important that the power supply is efficient and has low electrical losses.

The Low Cost Power Supply IPD team consisted of three electrical engineers/technicians from ITT, the VP of purchasing, a purchasing manager, three representatives from manufacturing, and two representatives from QA. The bulk of the work was performed at the site of the supplier of the power supply, K and M Electronics in Springfield, MA. They had a team of approximately six electrical engineers working on the project. The author started in the role of managing the schedule and moved to the role of Program Manager midway through the internship (the project is still ongoing and a new Program Manager has been assigned this role).

2.2 Applying Critical Chain at ITT Night Vision

2.2.1 The Assignment and First Training

The impetus for this project came from Neil Gallagher, then General Manager of ITT Night Vision. He is a Goldratt Institute certified “Jonah” and had read Eli Goldratt’s newest book, *Critical Chain*. “Jonah” is the highest designation given by the Goldratt Institute, and is dubbed after a character from Goldratt’s first novel, *The Goal*. Gallagher and Stephanie West, Vice President of R&D Engineering, both agreed that the division was suffering from project schedule problems. They did not feel they could consistently bring projects (particularly product development) simultaneously in on time, within budget, and/or without cutting scope. West and Gallagher tasked the author with implementing CC on both INOD and LCPS as pilot projects and then disseminating the lessons learned from the experience as broadly as possible. Within the first week of the internship there was a one-half day Goldratt Institute seminar on site attended by ITT Night Vision’s Senior Staff, project managers, and other key team members. Key individuals from K and M Electronics also flew down for this seminar.

The author, along with others at ITT, read *Critical Chain* and did further research on the new methodology. As in *The Goal*, the book is written as a novel, which makes for easy reading. Goldratt weaves the theory of CC into the story of an MBA professor who is fighting for tenure and teaching an executive level project management course. Although Goldratt presents the concepts, the book does not provide a complete basis to implement CC in industry. Elton and Roe point out:

> “But while the factory setting in *The Goal* established a realistic context in which to develop and test the theory, *Critical Chain*’s academic environment does not sufficiently bind together the various real-world vignettes. As a consequence, the reader is presented with hearsay evidence rather than given the opportunity to work through a full application of the theory during the course of the book.” [Elton and Roe, 1998]

Furthermore, although the book does a decent job describing how to apply CC to a single project, little is written about the more realistic scenario of applying the Theory of Constraints to multiple projects competing for the same resources. This deficiency further reinforced the belief that extensive training and benchmarking would be necessary to implement this new tool successfully.

2.2.2 The Second Training Session

After the government awarded ITT the Integrated Night/Day Observation/Fire Device contract, the author took over as the Goldratt Institute point of contact. A two-day Critical Chain training workshop was scheduled for July 21-22. This was attended by all of Night Vision’s senior staff, all project managers, most members of the INOD and LCPS teams, five individuals from K and M, and one individual from Leica. ITT paid for all participants to attend the training and workshops. Unfortunately, the desired people from the INOD Leica team were not available and this was costly later in the project. This training session was much better than the previous one and cleared up most of the theory of CC, both as it applies to single project and multiple project implementations. Goldratt incorporated hands-on scheduling “experiments.” These were useful in reinforcing concepts, but the “proofs” of the CC concepts were less than scientific (the “experiments” were rigged). Overall, this two-day session accomplished an enormous amount in giving the stakeholders of both pilot projects a common vocabulary and understanding of the concepts.

2.2.3 The Network Building Workshops

The week of August 4, a network building exercise was held for both projects with Goldratt consultants as the facilitators. Two and one half days were spent on each project. Eight individuals, including the Vice President of R&D, attended the INOD workshop. Unfortunately, again the desired Leica people were not available and another fill-in was sent over from Switzerland. This turned out to be costly (involving downstream overhaul of the network) because the Leica portion of the CC ended up being quite large and it was difficult to nail down accurate task estimates and dependencies. Four ITT and four K and M employees attended the LCPS workshop. The format for each workshop was the same.

The first half-day of each workshop was spent identifying, as a team, the overall goal for each project. This might sound like a lot of time to invest in merely identifying the project’s objective, but it ended up being quite powerful. The LCPS team had been working on their project for at least 3-4 months, yet there was little agreement on the specific goals (objectives which would define successful completion) of the team, other than to significantly reduce cost. The facilitators emphasized that the final objective of both teams should be to increase the throughput (money making ability) of the company. This is a core principle of Goldratt’s TOC, the goal of a manufacturing company is to make money and team objectives should be tied to increasing this ability. Thus, the INOD team goal was not to successfully build six prototypes. The designing and building of the prototypes was awarded as a cost-plus contract, which means ITT will make little or nothing on it. The true value of the contract comes when the company wins the production build of 2000 units and the customer’s needs are fulfilled. Thus, the purpose of the team was written as doing whatever was necessary to get ITT to the point where it is in full production of INOD units and generating profits.

The goal of the LCPS team was even more difficult to capture because there were two companies’ stakes to reconcile and put into words. Everyone realized that the team would not be deemed successful if ITT simply negotiated a lower price from K and M and drove them out of business. As partners, we wanted to identify a win-win design that could improve the bottom lines of both companies. The objective of the team was agreed to be when ITT and K and M are in full production with “a design that meets ITT’s cost and K and M’s profit objectives; comparable if not better quality and yield for both ITT and K and M; and the ability to make weekly shipments.”

The next phase of the workshop took about one and a half days and was aimed at building the projects’ task dependency networks. This was accomplished by working backward from the previously defined goals of the teams. The facilitators asked the teams what predecessors were necessary to accomplish their final objectives. They really emphasized what <u>must</u> take place as opposed to what would be nice, in an attempt to break down existing paradigms of how similar projects had been accomplished in the past. The original INOD and LCPS schedules had followed the templates from past schedules which ended up adding unnecessary finish-start constraints (such as finish-start constraints due to resource limitations or due to convention).

In this manner the teams worked backward through the entire schedule until all tasks necessary to successfully complete the project had been identified and placed in their proper context. Large chunks of the schedule were given to two or three subject matter experts within the team to be broken down into finer detail. This saved time by allowing more than one area to be worked on simultaneously. Once a group had completed their section, they would present it to the rest of the team for approval. Breaking the schedule into finer detail allowed for more overlap and parallel work, thus shortening the CC. The facilitators used the term “good enough” when it became obvious team members had reached the point of diminishing returns and were breaking down tasks into detail which would not facilitate further overlapping.

In order to deal with necessary iterations the team attempted to determine the average number of iterations that would be required and built that number into the network. Thus, the iterations were converted into a linear set of repetitive tasks in series (i.e. “Preliminary Optical Design,” “Intermediate Optical Design,” “Final Optical Design”). As the team was defining the network, one of the facilitators entered it into her laptop and printed it on 8½” by 11” sheets, which were taped together. The INOD network had 187 separate tasks (Figure 12), the LCPS network had 106.

Figure 12: The INOD Network

The last half-day of each workshop was spent assigning to each task the resources necessary to complete it and the average time needed to complete it. This phase of the workshop went much more smoothly than was anticipated. Resources were assigned as a team; this seemed to clarify roles and interactions as the projects were executed. The teams attempted to identify the minimum number of people necessary to complete each task. If a resource was deemed to be needed for less than 10% of their time, they were considered a consultant to the task and not captured. The team tried to stay away from assigning partial resources as this seemed to go against the CC theory and made tracking the project more difficult.

The Goldratt consultants had the team agree to three ground-rules to be kept in mind when determining average times:

1. You have all the necessary resources and inputs before you start work.
2. You work only on the assigned task non-stop until it is complete.
3. Either give your best estimate of the median time or give the “95% time” (C) and cut this time in half.

All members of the team gave estimates for each task. Amazingly, with the above ground rules, most estimates for the same task were within a few days of each other. It seemed resources could give more uniform task time estimates when they were not, in the back of their minds, taking into account the time other competing projects would demand. Often the person who would be performing the task would give the highest estimate and the other team members would ask him to defend his assessment. Many times the primary resource would admit there was still “padding” in his estimate and this would lead to a consensus with the rest of the team. Peer pressure seemed to be an effective tool to push back against high estimates and drive out all safety. This worked well for the INOD team because it happened to all team members and no one felt like he was being singled out.

LCPS was much more difficult. K and M personnel would be performing most of the tasks and thus, they were making very large time estimates compared to what the ITT people expected. It appeared K and M anticipated ITT would micro-manage the project, and that they were expecting to be held accountable individually for each task completion time. It was also obvious that many of the internal processes K and M personnel were using would not support rapid product development. As an example, two weeks was originally given as a “50/50 time” estimate just for *ordering* sample parts to make the preliminary breadboard. The K and M engineers insisted that all purchased parts, no matter the quantity, must go through their purchasing department, which has a two-week backlog. ITT’s engineer contended that he could call a distributor and have most parts within 24 hours. CC highlighted the impact of excessive administrative “rules/red tape” on product development. It accentuated the need to examine even the “non-technical” issues in order for a company to be agile.

The Goldratt facilitator eventually decided not to dispute the K and M estimates, just so the K and M representatives could see how ridiculously long the total CC would be. As it turned out, this tactic proved to be very effective. The preliminary LCPS Critical Chain was more than two years long. When the K and M team recognized this, they acknowledged that they would have to make changes in order to remain competitive. They were much more willing to revise their time estimates in a later iteration.

Another lesson learned from the network building workshops was that it seemed to be more difficult to lay out a network when the direction the project would take was less certain. INOD was well defined because the government specifications were quite specific, and a preliminary design had been done for the proposal. The LCPS schedule was more difficult to agree on because of both the differences of opinions of the two companies involved, and the vagueness of the design direction the team would pursue. For this reason, the team ended up putting together two parallel networks, only one of which would be used after some initial design decisions were made.

2.2.4 Concentrating on the Constraint: Shortening the Critical Chain

After getting through the initial cut at each project's network, resources were de-conflicted and the CC for each project was calculated manually. Next, the teams spent time trying to take time out of the CC. This was primarily done by challenging assumptions on task dependencies and on resources required. Tactics used included breaking unnecessary finish-start constraints, exploring alternative resources, exploring ways to streamline the work (remove the "waste"), adding resources to CC tasks, breaking CC tasks into smaller tasks to allow greater overlap, and challenging original CC "50/50 time" estimates.

The CC on the LCPS project with project buffer was originally calculated to be 529 workdays; after the first iteration it was down to 305, a saving of almost a year. Although the first LCPS schedule was probably not realistic due to the long original estimates, many assumptions would never have been questioned had it not been for the emphasis on shortening the CC. The first INOD CC was more than 560 workdays in length; it eventually was whittled down to 141 days with a 22-day project buffer (due to contract constraints). Shortening the CC was iterative, much like breaking the bottleneck in a manufacturing setting. Once the CC was shortened, the schedule was recalculated to see if the constraint had shifted. Next, the team would focus on shortening the new CC. This continued until the teams felt they had reached the point of diminishing returns.

One example of how concentrating on the constraint got the teams thinking ahead related to the INOD optics. Leica customarily would finish an optical design before ordering any raw glass for the prototypes. Apparently, some of the glass they use is fabricated by their supplier as rarely as twice per year. They estimated a realistic "50/50 time" for receiving all of the necessary glass was 40 workdays. This 40 days ended up being a large portion of the CC. This delay meant the project would not make its due date. When the team questioned the Leica people about this, they replied that there was nothing they could do to accelerate the task. Finally, we asked what it would cost to order all possible specialty glasses that might be necessary after the preliminary optical design, instead of waiting for the final design. The Leica person originally said this was risky because there was a good chance they would not use all of the glass ordered. The estimate came to roughly $2000, which is a small amount to risk in order to bring a $3.2 M design effort to completion eight weeks earlier. ITT and the INOD customer readily approved this advanced purchase.

During the workshops, the Goldratt consultants computed the dollar amount to ITT for every day the projects came in late or early. In general, it seemed to be very powerful for the members of the teams to be conscious of the exact value to the company per day of schedule variance. When finished, the LCPS project will save ITT Night Vision thousands of dollars per day. Once the team realized this, it was much easier to argue for changing standard practices to bring the project in a few days or even weeks earlier.

The LCPS detailed design officially started on August 19, after a meeting between K and M and ITT that decided which system architecture the design team would pursue. By this point, the CC had been worked down to 173 days. The project buffer was set at the Goldratt recommended 50% (87 days). Thus, the date committed to senior management for completion of the project was November 18. This was less than half the length of the first schedule that came out of the network building workshop. It was also months shorter than the original schedule (before the introduction of CC), and nobody felt confident the original schedule would be attained, given the lack of alignment on design approach.

In mid-August, the lead engineer from the Leica team was finally available and met with the INOD team. Unfortunately, he disagreed with many of the schedule inputs that had been made for him by the stand-in. He disagreed with both the time estimates and the structure of the network (i.e. how they were going to approach the design). This caused a lot of rework in the schedule and confusion among the team. The INOD Initial Process Review (IPR) was held on August 28. The day before was the first time the team met the Program Manager for the Leica team, and he again completely revamped the schedule. Overall, I estimate that not having him at the initial schedule workshop caused a six-week delay in implementing CC for this project, along with many hours of schedule rework. This affected the end-delivery of the product only inasmuch as it created schedule confusion and a distraction for the team.

The final INOD Critical Chain was eventually shortened to 141 workdays remaining after the Initial Process Review (IPR) completion (see Figure 13). This should have demanded a 72-day project buffer. Unfortunately, the March 24 contract date for delivering the six prototypes only allowed a 22-day project buffer. It also left the team wondering how to present the schedule to the government. Many on the team were concerned that if the government was shown a schedule which contained a buffer they would feel the buffer was unnecessary and ask for a quicker delivery. These people argued we should keep two sets of schedules, one for internal use and the other to present to the government. This would not only have been time consuming, but also could have been confusing and led to problems between the government and the team (team members might reference the wrong schedule during government discussions). In the end, it was decided to give the government team a one-hour training session on CC during the IPR and then deal only with CC schedules. This also enabled the team to show the government how the shortened project buffer lowered the probability of finishing on time. Although it was initially rather awkward, the customer did become more comfortable with the CC approach. After several months, the team sensed a tremendous breakthrough when reviewing the project’s status with the customer. The government Program Manager asked, “What is the status of the buffers?” instead of asking for specific milestone completion dates.

Overall, the process of concentrating on reducing the CC in conjunction with making the teams aware of the additional profit to the company for each day saved seemed to be very effective. However, this is also the premise behind the CPM.

2.2.5 Working with Microsoft Project and ProChain

After the INOD Initial Process Review, the author’s primary objective was to enter both schedules in MSProject and learn the software that supports CC, called ProChain. This is a macro which runs with Project and disables many of the automatic features of Project which are counter to the CC theory, such as scheduling all tasks as early as possible. It also adds six additional icons to the Project toolbar, which will be described further in chapter four (see Figure 17). As ITT was one of the first users of CC, we were using a beta-copy of the software. Coming out of the schedule workshops, the

Goldratt facilitators left ITT with only the 8½" by 11" printouts of their MacFlow networks. These networks were each about 20 pages and had to be taped together in the proper sequence in order to get a graphical representation of the projects' PERT charts. As changes were made to the schedules, they were done by hand in red pen to these taped together printouts. Obviously, this was not an optimum system. Once the schedule was entered into Microsoft Project's PERT format, the team was able to make changes and print the entire schedule on the CAD plotter.

Also, before receiving the ProChain software we were trying to use MSProject on INOD (due to contractual requirements) by forcing the schedule to match our hand-calculated CC using must-start-on constraints. The author spent weeks trying unsuccessfully to convert this schedule into a working ProChain schedule. Finally, on October 2, ITT brought the writer of the software on site both to train users and debug our schedules. This proved invaluable; by the time the ProChain developer and his partner left, ITT had two working schedules and understood how to use the software to keep the schedules current and dynamic.

Although attempts had been made to manage both projects using manually calculated buffers, the primary concentration had been on the project buffers. By the time both ProChain schedules were working, many of the feeder buffers were severely depleted, especially on the LCPS schedule. Once ProChain schedules were on-line, the software calculated all buffers with each update and greatly facilitated managing the projects using buffer analysis. The software greatly eased the job of managing, tracking, and representing the schedules for the teams. It transformed a full-time job into a few-hours-per-week task.

2.2.6 E-mail Updates

The author updated the progress on both schedules three times per week, although Goldratt recommends daily. Each non-ITT person (Leica and K and M) who was working on a task was supposed to send a one-line E-mail at the close of business on Mondays, Wednesdays, and Fridays. This E-mail simply stated how many days they had left on the task they were working. If there was a major slip, they would include a line or two explaining what had happened. Although many wanted to provide an expected completion date and then only E-mail if this date changed, we resisted this temptation. Dealing in due dates can reduce the sense of urgency and lead to student syndrome or multi-tasking. It also is more convenient to submit the expected due date repeatedly rather than calculate how much time is actually needed to complete a task. By continuing to work in durations, it helped all of us to make the paradigm shifts that are necessary for CC to be successful. Also, the numerous updates acted as a reminder that team members should only be working on the assigned task and not be multi-tasking. Lastly, the frequent updates helped catch problems and enabled us to react to them immediately.

2.2.7 Red and Yellow Pieces of Chain

Another innovation the author implemented was physical CC reminders to the team. A red piece of chain was hung on the door of resources working on the CC task for each project (CC tasks are colored red on the Gantt charts). This acted as a "red-light" reminder to all other employees that the person was working on an important task and should not be disturbed. It also acted as a reminder to the resource that he should work only on the CC task. Lastly, the red piece of chain was used analogously to a baton in a relay race. When a resource would finish a CC task they would hand the chain and any other deliverables to the resource/s assigned to the next CC task. This way, there was never any confusion among the team as to how far the schedule had progressed or who was on the CC.

We also hung yellow pieces of chain on the doors of resources who had less than five days until they would be working on CC tasks (resource buffers/readiness alerts are colored yellow on the Gantt charts). These acted as signals to caution other project managers that the person soon would not be available for non-CC work, and should wrap up any other tasks he was working. Red and yellow pieces of chains were also sent to Leica and K and M and apparently were used in the same manner. Appendix B is an E-mail the General Manager of ITT Night Vision sent to all employees and shows how seriously management took both CC and these chains.

Amazingly, team members really liked the idea of the pieces of chain. Many people outside of the INOD and LCPS projects asked for red pieces of chain so they could keep people from bothering them and concentrate on one task until it was complete. The chains also gave team members a sense of importance because they were working on the most critical tasks. At one point, the INOD project ate into the red zone of its project buffer and it was decided that CC resources would have to work weekends until the buffer was back in the yellow zone. Despite this, INOD team members still wanted to get their hands on a piece of red chain. Furthermore, this policy and CC helped somewhat to reduce worker burnout. Had it not been for CC, the entire team would have been required to work weekends once the project fell behind, CC helped pinpoint exactly which team members could catch the project up.

2.2.8 Automatic E-mail Responses

Another feature the author implemented was automatic E-mail responses for resources working on CC tasks. This was quite simple to set up. Our server would respond to every E-mail sent to a CC resource with a short message that read, “This person is working on a Critical Chain task that is estimated to be complete in ‘X’ days. You might not get a response to this message until work on this Critical Chain task has been completed.” This feature was not as well received as the chains and few team members used it. Resources preferred to read their E-mail as they received it, and personally responded to each message even if they were supposed to be working on a CC task. This is an issue that will need additional attention. Clearly, reading/responding to E-mail (like reading/responding to hard copy mail in your in-box) is essentially multi-tasking and can significantly detract from time that should be dedicated to working on CC tasks.

Lastly, the author gave weekly buffer updates to the Senior Staff of Night Vision. These updates conveyed all the information the Senior Staff theoretically needed to know about the schedule status. An example of one of these buffer updates is shown in Appendix C.

2.3 Project Results

2.3.1 INOD

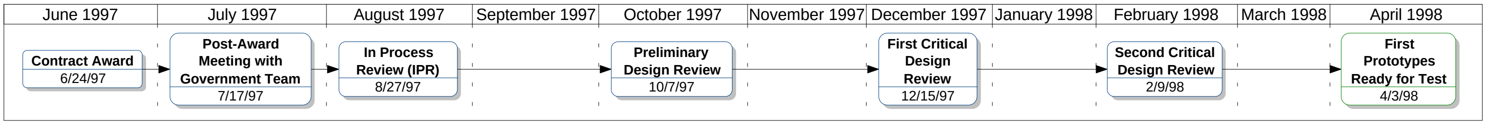


Figure 13: INOD Timetable

The INOD project followed the standard defense contract template, which calls for numerous design reviews with the government experts. The project was at a high risk of schedule slippage from the start. It had an extremely aggressive schedule, which was compounded by the fact that little technical progress was made the first six weeks after the contract was awarded. This was due to the uncertainty of when/if a contract would be awarded (it is typical to receive very little to no advance notice). Thus, there were the normal issues of reassigning resources upon contract award, training the team, getting the program documents in place, and preparing for the post-award contract meeting with the government team. Schedule risk was further compounded by the long European summer vacations of the Leica partners. Due to the necessity to plan periodic government reviews ahead of time, the team was forced to break up the already small project buffer into three pieces. Some project buffer was placed in front of the Preliminary Design Review (PDR), some was placed in front of the Critical Design Review (CDR), and the rest buffered the final deliveries of the prototypes.

The PDR was held October 7-8 as scheduled. At this point, the team did not have as much of the design completed as had been scheduled, but the review went very well. Again, the schedule was presented in CC terms (with a little more government CC training). At the PDR, the team had only a 13-day project buffer and it was pointed out that with 94 days of CC work left, there was a high risk of missing the completion date.

The government users felt that the specification for the diameter of the large Afocal was too large after seeing the wax prototype the team had made. However, even given this tight schedule, the government directed the team to readdress the performance requirements. They redefined their specification and asked Leica to redesign the large Afocal. The government users stated that they would accept whatever performance the new diameter would allow.

Although the team contended that it most likely would not be ready until the first week in December, the government mandated at the Initial Process Review that the Critical Design Review be held just prior to Thanksgiving. As it turned out, the ITT Program Manager was later forced to request a postponement until the first week in December so the team could be more prepared. Due to government conflicts, the CDR was held December 15-16. Fortunately, the team had thought ahead and planned to release the design of the parts which lay on the CC prior to CDR anyway in order to immunize the project buffer from delays in the CDR. Thus, the delay of the CDR did not translate into a day for day consumption of the project buffer. At the CDR the design of the reticle/eyepiece assembly was still not complete. Furthermore, the users were not happy with the performance predictions for the redesigned large Afocal and asked that it be redesigned a third time (back to the original diameter). Lastly, for reasons unknown to the INOD team, the State Department decided that the image intensifier tubes could not be exported to Switzerland to be installed into the super-modules as has been planned. They would not even allow optical slugs (tube simulators) to be sent over so Leica could align the systems and then ITT could replace the slugs with tubes in the U.S. This severely impacted the schedule. The combination of these three factors resulted in the government asking for a second CDR.

The status of the recalculated project buffer against time is shown below in Figure 14. The author has attempted to negate the effect of the government-mandated changes to the specifications of the large Afocal by tracking only when the medium systems were ready for testing. This is still not entirely accurate because the large Afocal redesigns consumed the efforts of the team's constrained resources causing the medium system finishes to be delayed.

At point 1, the team rebaselined the schedule after falling into the "red" (act) area of our project buffer (because the initial project buffer was small due to schedule constraints, the buffer was divided only into "yellow" and "red" zones). This entailed breaking some finish-start constraints by removing a non-essential product risk reduction effort and adding new resources to help with CC tasks. At point 2, the CDR was declared incomplete and the team had been informed that the image intensifier tubes would have to be installed by ITT. After point 2 the team again rebaselined the schedule with the new information, but these changes did not increase the medium system delivery buffer. Instead, the emphasis was on finishing the large systems as quickly as possible. A new completion date, which included 50% of the remaining CC for a project buffer, was calculated and submitted to the government.

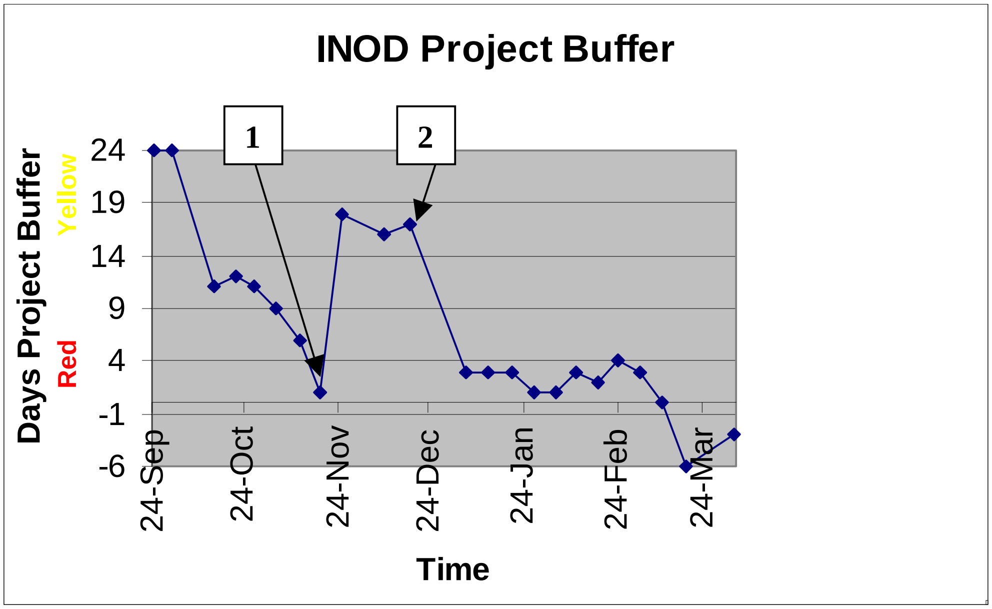


Figure 14: INOD Recalculated Project Buffer Against Time

2.3.2 Low Cost Power Supply

The LCPS project went much more smoothly, partly because it had the luxury of starting with the recommended 50% project buffer, there were no pre-imposed interim milestone dates, and there were no export license issues. Eighteen days of project buffer had been consumed since the start of the project by the first time the schedule was completed. The buffer should have been 109 days and was down to 91. The project buffer soon shot up to 112 days because ITT's electrical engineer was able to find and order most of the breadboard parts instead of having to send the order through K and M's purchasing department. Many of the feeder buffers had been consumed by the time the author was able to get the schedule working with the ProChain software. K and M had intended to hire three additional electrical engineers to support this project and had been unsuccessful. This caused major resource constraints. Since management was concentrating on the CC, the CC tasks were being completed; feeder paths were not focused on because the team did not have a mechanism in place that readily portrayed this data. This ended up being a problem because nearly all the feeder buffers close to the start of the project were in the "red zone" by the time they were being accurately tracked.

With the ProChain software properly tracking the status of all the buffers, it was much easier to see which were the most critical tasks to emphasize. It also helped make a good business case to K and M management that helped speed up the hiring of the additional resources. ITT had at least one telephone conference with the K and M team per week and traveled to K and M's site about once per month. It was interesting to note that K and M seemed not to admit during the telephone conferences that they had as much work completed as they really did. They seemed not to want to admit that they were as far along as they were, so that if they ran into trouble, they would still have some buffer. The ITT team was usually happily surprised at how far along they were during site visits and the project buffer would grow accordingly. The graph of the project buffer against time with the buffer zones depicted is presented below. This project has not yet completed, but is going very well. It has 52 days of PB remaining.

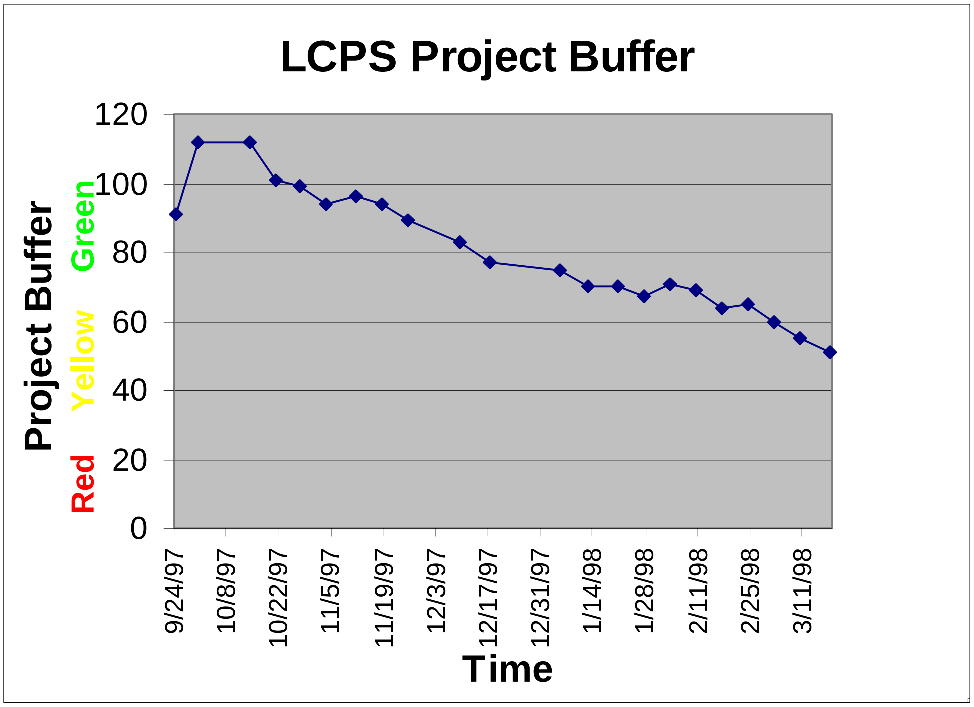


Figure 15: LCPS Project Buffer Against Time

2.3.3 ITT Night Vision Facility Expansion

About six weeks before the author was scheduled to leave ITT, the Vice President of R&D assigned a full-time employee to replace me as the CC champion to ensure a smooth transition and continued success of CC at ITT. Jim Utterback took over the CC duties mid-December. At that time ITT was also working on a facility expansion which would double their output to meet increased night vision demand. This is a multi-million dollar project critical to Night Vision's future success. The General Manager had decided early on that he wanted to use CC to try to bring this project in as quickly as possible. The team had been working with the Goldratt consultants to implement CC, but the tool was not being effectively utilized due to a lack of emphasis and software problems. Utterback and I began working with the facility expansion team to get their schedule entered into MS Project and start tracking their buffers. This project was interesting for this research because it was a larger project with more resources involved. There were roughly 100 people working on the project and it had 218 tasks. The project was large enough that it was not feasible to get the whole team together at one time for a network building workshop. The project leaders broke the project into ten high level chunks. They then had different teams put together a CC schedule for the various pieces. Once this was complete, it was not difficult to tie the various CC schedules together to obtain the CC for the entire project. This is how the author would envision scaling this tool up for use on much larger projects. This is also similar to how the INOD team broke its project into the two phases of the project. The facility expansion started with only 16 days of project buffer. It has progressed well and still has 11 days of project buffer remaining. The team has used overtime and worked weekends to keep from consuming project buffer, although one has to wonder if the network was constructed with realistic "50/50 times." Far fewer than 50% of the project's tasks have used more than their allotted task duration.

2.3.4 Project Lessons Learned

The INOD project was difficult to manage due to the fact that it started with far less than the recommended project buffer and the government mandated milestones forced the team to track intermediate dates. Furthermore, although I have tried to correct the presented data for the government mandated specification changes, these still slowed the team's progress across the board. Since it is believed that the artificially small project buffer drove the team to poor decision making, given the same circumstances in the future, I would instead use the Goldratt recommended buffer sizes regardless of the time constraints. Reducing the project buffer shortens the length of the project on paper only. At best, it can increase the team's sense of urgency, at worst it can put the team under such time pressure that morale suffers and poor decisions are made. Instead, I would have presented at the first government meeting that the team would do anything possible to finish the project before the contractual date, but I would manage the team starting with the full buffer sizes.

Another lesson learned is that cultural differences must be taken into account when scheduling a multi-national project. The Swiss take a six-week summer vacation that fell right at the beginning of the INOD CC. The last lesson learned was that it is critical to have the right people at network building workshop.

For reasons noted in Section 2.3.2, the LCPS project proceeded more smoothly. Initially it required high-level management interfaces to emphasize to K and M the seriousness of ITT's intent to implement CC and convince them to participate in the training. It was also critical that ITT paid for the training. As it progressed, the K and M people increasingly seemed to accept CC and the fact that ITT was serious about using it. Their management must have been impressed by the results of this project. They have set up a relationship with the Goldratt Institute and will apparently be using CC on all their new development projects. Another factor key to the success of LCPS was that ITT had independently designed improvements to the power supply and was willing to share improved alternative ways to address both technical and non-technical issues.

One fact of project management that neither CC nor CPM handles well is unplanned iterations, such as the redesigns of the INOD large Afocal. The CC buffers cushioned some iterations, but were not large enough to absorb major iterations. The only option a project manager has is to increase the sizes of the buffers, but this will leave projects that avoid large unplanned iterations finishing well ahead of schedule. Although finishing early is usually not looked upon as a problem, there are many cases (such as timing a market introduction) where predictability is very important. In the end, project managers will have to use their experience to optimize the sizes of the buffers for each project.

2.4 Benchmarking Studies

In order to have both quantitative and qualitative comparison data, the author conducted two benchmarking studies. The first was a study of all product development projects ITT Night Vision had undertaken for the three years before implementing CC. The second was a benchmarking study of Harris Semiconductor, another lead user of CC.

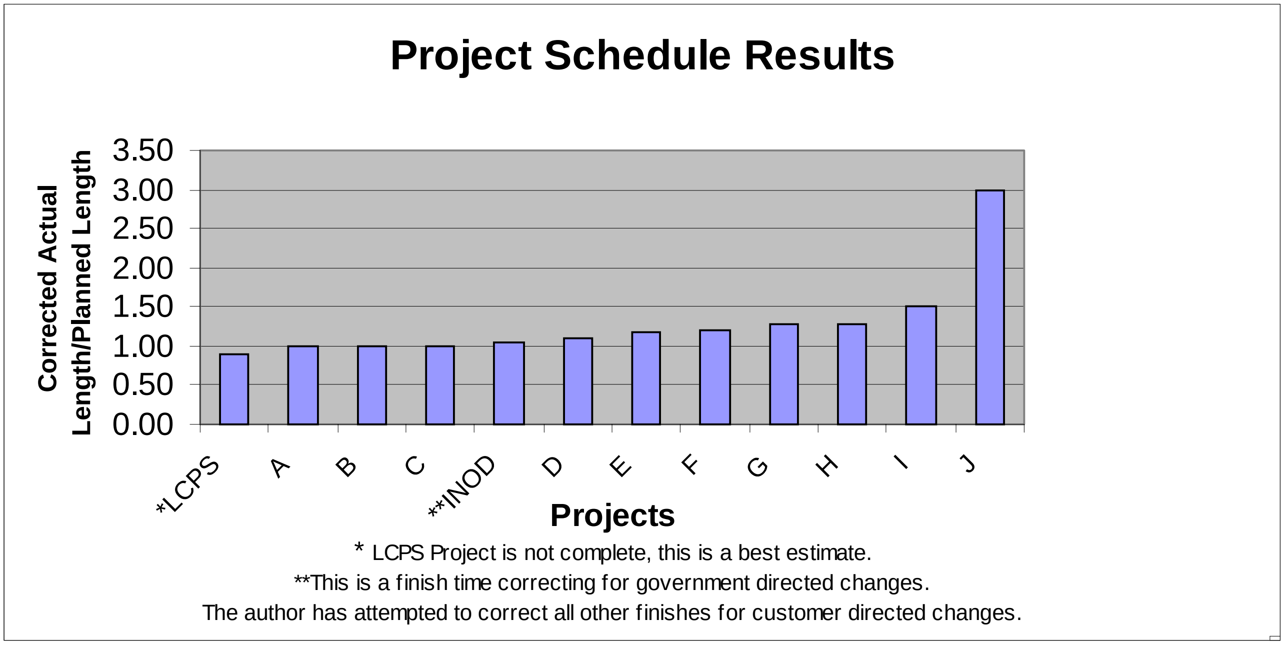
2.4.1 ITT Internal Benchmarking

The internal benchmarking study consisted of interviewing the technical, finance and marketing contacts for the ten prior product development efforts. These projects vary widely from complex new product development efforts to relatively minor modifications of an existing product. The author conducted 15 interviews that lasted from 30 minutes to one hour each. For the purposes of this paper, it is not necessary to understand what each of the projects entailed. Due to company confidentiality, a single letter represents each project.

Unfortunately, much of the quantitative data, particularly the financial data, were difficult to obtain within the time constraints of this research. The internal accounting system had not been set up to provide detailed profit or expense data for all of the individual products, and some of the data that had been collected was no longer readily available. If project managers set up segmented (as in a detailed Work Breakdown Structure) expense accounts to track all development expenses, the use data would have been available, but this had not been the practice. All projects have an account number assigned, but some of the projects studied used only one or two sub-accounts. Others used 40 or 50 to attempt to delineate costs into logical work segments. Clearly, discipline in assigning and tracking against multiple subtasks is less when the project is relatively small and is internally funded. The government-funded development projects mandate that budgets, and costs are segmented. The benchmarking study did point out that some projects costs were difficult to track, and it has subsequently been impressed upon the project managers that they should more clearly track all development costs.

Some of the schedule data were also less than clear. The author had intended to compare actual project durations to planned project durations to normalize all projects for comparison to the INOD and LCPS results. The nature of government contracts for product development or for production can make this very difficult to do. As in the INOD project, there are quite often government specification changes during the design effort, which delay the final design. Furthermore, these government changes are often difficult to segment from internal schedule delays or costs because the issues tend to be inter-related. Every effort has been made to correct the data for these government induced schedule overruns in order to normalize the projects. Inherently, participants' opinions of the magnitude of schedule slip prior to government changes seemed to vary across the same project depending on the role they filled for that project. The results are further skewed because the author was much more familiar with the INOD and LCPS projects and better able to correct their final results for all customer mandated changes which forced a schedule slip. This is particularly true of project J, customer directed issues were a major factor in managing this project and the author's lack of intimate knowledge of their impacts made it quite difficult to precisely adjust for them.

In addition, many project managers had not baselined their original schedules to final results and had not saved their original schedules for comparison. This is partially due to inherent weaknesses of Microsoft Project and the initial uncertainty of externally funded product development efforts. If the project manager baselines the initial schedule before project details have stabilized, it can become cumbersome in Microsoft Project to redefine tasks. Hence, project managers avoid baselining and the schedules become less meaningful. Nevertheless, the author has made his best effort to normalize the schedule performance of the ten projects. The results are shown below.


Project Schedule Results

* LCPS Project is not complete, this is a best estimate.
**This is a finish time correcting for government directed changes.
The author has attempted to correct all other finishes for customer directed changes.

Figure 16: Product Development Schedule Results Including INOD and LCPS

The mean normalized finish was 1.35 (meaning that the average project took 1.35 times as long as planned, after correcting for government mandated changes). To put things in perspective, it should be noted that this is far superior to the defense industry standard. LCPS has 51 days of buffer, with much of the remainder of the CC consisting of a 90-day government reliability test. Extrapolating the rate at which the project has been consuming buffer yields an expected final project buffer of 30 workdays, or a 1.5-month early finish (.90 when normalized). The first phase of the INOD project was considered complete for the purposes of this research when the medium systems were ready for testing. This corrects for the government mandated changes to the test schedule and large Afocal design. This yields a half-month late finish, or a value of 1.06 when normalized. Due to the high variability of the finishes, the standard deviation for the sample is quite high at .60. Thus, although both INOD and LCPS are expected to finish below the mean for the sample, the results are not significant at a 95% confidence level. The difference between the means of the two sample sets (pre-CC projects are one set, INOD and LCPS are the other) is also not significant when they are tested with a single factor analysis of variance test (ANOVA). The F value is .714 and F critical is equal to 4.96.

A qualitative assessment of the schedule risk inherent in each project was gained by having interviewees categorize projects as either primarily existing parts or primarily a new design. Many of the design projects were alterations to existing products and were deemed to be less risky. Interviewees also categorized projects as having been directed by new or existing customers because it is felt that new customers can lead to a higher risk of schedule slippage. Thus, the highest risk projects should be those that are primarily new products for new customers. This intuition seems to be correct, except for project C, which finished relatively earlier than expected, and project I, which finished relatively later than expected. As can be seen in Figure 17, INOD and LCPS fall in the more risky quadrants of the risk matrix and would be expected to be at a higher risk of schedule overrun.

	Primarily Existing Design	Primarily New Design
Existing Customer	A B E I	G **LCPS**
New Customer	D H	C F **INOD** J**

***Although this product was intended for an existing customer segment, the requirement for the product to have dual configurations (for infantry and aviation use), integration with undefined equipment from other Prime Contractors, as well as the introduction of new technology, places this project as higher risk than any of the others studied.*

Figure 17: Mapping of Products into Risk Matrix

Based on the interviews, there were a number of common qualitative themes that emerged.

- Many projects were not fully staffed immediately after the contract award (see Footnote 3). Often the start-up delay was equal to or greater than the amount the finish date was delayed.
- Most schedules were written assuming the project would be fully staffed and fully productive on the first day.
- In some cases contract labor was added to a project team late in the project as part of a “recovery schedule.” Often this tactic was not as effective as hoped. In some cases by the time the new team members were up to speed the project was complete (and it takes an investment by the original team members to get new team members up to speed, which Cooper has shown can actually slow a project down.[Cooper, 1994])
- In some cases the delays associated with major government contract alterations are believed to be under estimated because they could not be clearly delineated and hence, not fully conveyed to the customer.
- It was stated that some of the smaller projects could have benefited from more detailed resource dependent schedules.
- In many cases required man-hours were underestimated (apparently due to unplanned iterations), while material costs were overestimated.

Although some of these issues may be inherent in externally funded product development, clearly there are common themes that CC can address. By providing a detailed project network that incorporates consideration of specific resources, a more realistic schedule is developed. This basic network can also be used to generate resource "what if" scenarios so that the impact of investing in additional staff can be quantified (and thus minimize the tendency for conservatism in staffing levels). This can lead to more proactive staffing of projects as opposed to waiting until the project is at a very high risk of schedule slippage. Although the timing of new product development programs is sometimes out of the control of companies such as ITT[2], the CC network could be used to evaluate staffing scenarios based on a number of program start-up dates. This would provide valuable data for management to consider when additional new-business proposals are evaluated.

Furthermore, if the starting date of a project is uncertain, it is recommended that a fixed initial period of time be built into the schedule to allow for regrouping the team, getting team members up to speed, and initiating program activities.

It was noted earlier that some of the projects were bid with only a top-level schedule. This is generally attributed to two factors. First, the level of uncertainty regarding project scope and approach may be significantly high and creating a hesitancy to invest a great deal of energy in trying to develop a more detailed schedule. There may realistically be so many unknowns that a detailed schedule is not viable until additional discussions are held with the customers and team members. In a competitive contract award process, a "curtain of silence" is mandated and industry is prohibited from having any discussions with the customer until after an award decision is made.

Second, project leadership may sometimes be assigned based on technical skill (especially for advanced development or internal research and development work) and not on project management ability. For smaller projects, a project business manager might not be assigned. In these scenarios, the technical lead tends to be a very experienced technical manager who will generally know the comprehensive work that must be done. However, it is the author's observation that if that manager develops the schedule on his or her own, essential non-technical considerations will be omitted and often to the detriment of project completion. If schedule management is important, the investment must be made to assign project managers to these kinds of projects and have the teams put together detailed project networks.

2.4.2 Harris External Benchmarking

The Harris Semiconductor benchmarking was also quite valuable to the author's research. Harris has encountered many of the same successes and setbacks with implementing CC as has ITT. Harris Semiconductor first used CC to manage a major facility expansion, the first-ever eight-inch discrete power wafer fabrication plant. They nicknamed the project "Raptor." The industry norm for a new fabrication plant from breaking ground to first silicon is 28-36 months; they accomplished theirs in 13 months. The industry norm for ramping production of a new plant is 18 months; they accomplished this in 21 days. The project started with a two-month project buffer and completed with three or four days remaining. By all measures, this project seems to have been an overwhelming success.

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[2] Government-funded programs are often awarded with very little or no advance notice. This leaves company management scrambling to reassemble a project team that may have been reassigned one to twelve months earlier when the program's proposal was submitted.

Following this success, the Harris General Manager decided to apply CC to all of their product development efforts. At this point they decided to apply CC to all product development projects at once. They made a large investment of both time and capital. Harris spent about six months training the essential managers and has just recently started using CC in product development. There are some major benefits to this approach. When a new tool like CC is used on just a few pilot projects, there is always the risk that even if the projects are very successful, employees will feel that the success is due to the extra management attention the projects received and not the new tool. On the other hand, it takes a lot of management stamina and courage to apply a new tool to everything at once and this approach also has significant potential problems. When a new tool is implemented across the board, it can be perceived as just another “program of the month” or as a “silver bullet solution.” The culture at ITT has been to implement new tools first on a pilot basis, allowing “lessons learned” to shape the application of the tool for future projects. This has helped create broader buy-in as the teams play a significant role in “shaping” the new tool or process, and has provided greater flexibility. This approach has benefits, but requires continual discernment and persistence by the “change agents” not to let early problems from the small sampling base thwart future gains. If Harris had not had their Raptor success first, it is doubtful that they would have taken the all-or-nothing approach they chose.

Many of the same cultural impacts of CC were experienced at both Harris and ITT. The project manager of the Raptor project commented, “It’s the soft intangible cultural things which often get overlooked which played a very, very important role in the success of Raptor.” He went on to state, “All of us knew we were going to win together or lose together like a team.” [Saxena, 1997] Even after the resounding success of Raptor and with the full support of the General Manager, implementing CC in product development has been a challenge. The Harris managers agreed that implementing a sweeping cultural change like CC is always difficult. As at ITT, many of their engineers have contended that “creativity cannot be scheduled.” It has taken longer for them to get up to speed than hoped, but all agreed that the rewards are well worth the effort.

Harris has also had many of the same scheduling experiences as ITT. “The task of building the network was quite challenging. This is where the bulk of the energy was spent in the early stages.” [Saxena, 1997] Unfortunately, most of the product development projects they have undertaken have not completed yet, but the management team is very optimistic. The manager in charge of product development stated, “Scheduled, it seemed like it (the project) was longer, but compared to historical data it will be much shorter.” [Saxena et al, 1998] Another manager stated, “Reliability of completed projects has gone up, predictability has gone up. Hopefully, compared to historical data, projects will be shorter.” [Saxena et al, 1998]

3 Critique of Critical Chain

Although Critical Chain has the ability to dramatically improve project and company performance, there are a few problems/shortcomings with the current Goldratt representation. This chapter will describe each of the practices Goldratt recommends, the benefits of the new approach, the shortcomings of the approach, and suggested improvements based on this research. Overall, the author concurs with Newbold and Lynch who wrote, “The authors believe it (Critical Chain) will become the most important improvement in project management since the development of the PERT and Critical Path methodologies.” [Newbold and Lynch, 1998]

3.1 Dealing in Average Task Times

Goldratt recommends building a project network with average task durations. He contends that people usually build safety into their individual estimates because their incentive is to finish the task within the given time, and they are being forced to pick one number from a probabilistic distribution. He advocates taking the task estimates that employees presently give and cutting them in half to arrive at reliable estimates for the average task durations.

3.1.1 Benefits of Goldratt’s Approach

Building the project network with average task durations is the first major improvement CC offers over traditional project management. Unfortunately, culturally, this is the most difficult change when implementing CC. By definition, if resources use average durations they will be late roughly half of the time. In effect, management is asking resources to give their individual task safety time to the team to be shared by all in the form of the project buffer. Obviously, for long-term success, incentive systems that reward individual resources for finishing their tasks on time must be reengineered. The alternative is that resources will continue to pad estimates randomly and that management will continue to cut them indiscriminately back down in order to remain competitive. What is left is a schedule with meaningless estimates that can not effectively be used as a decision-influencing model. Building the network with average task times seems to make more sense and be more useful for aiding in decision making.

3.1.2 Shortcomings of Goldratt’s Approach

Goldratt’s recommendation to cut all estimates in half in order to arrive at average task durations seems very arbitrary. Furthermore, without proper training this method could give resources the incentive simply to double their estimates. Particularly when dealing with highly mathematical workers, such as engineers, it is important to come up with a more robust formula for arriving at the “50/50 time.”

3.1.3 Suggested Improvements

At one end of the spectrum, resources can draw their estimation of the probability distribution for each task. There is software readily available which can calculate the duration that divides the area under the distribution in half. This would be the most accurate method available, but would also be quite time consuming. The noise inherent in task duration estimation makes this method seem like measuring with a micrometer and cutting with a chainsaw.

Another, slightly simpler, method would be to have resources estimate a few defined points on the graph of the distribution, such as the 5% time, 95% time and most likely time (mode). This data could be used to approximate the distribution, and again it would be simple to derive the average duration. Lucent Technologies is using a method similar to this to estimate the standard deviation for each task in order to calculate buffer size more accurately.

The least mathematical method available is to train the team, and then have resources directly estimate the median (50/50) task duration. Studies have shown that people give a median time even when asked to estimate an average time. [Kahneman, Slovic, and Tversky, 1982] The author used this method at ITT, and recommends it because of its simplicity and time efficiency.

It is not absolutely critical that resources arrive at the “right” average task duration. Particularly in product design, the variance in task durations is so great that there is inherent noise in the estimation. For CC to be successful, it is only important that the estimate is short enough so that both management and the resource feel a sense of urgency (avoid student syndrome), while long enough that employees do not feel that it is hopeless and give up.

3.2 Aggregating Buffer

The second major improvement over traditional project management Goldratt recommends is aggregating buffers both at the end of the project and at all intersections between non-critical paths and the CC. He recommends aggregating a portion of the buffer pulled from individual task estimates at the end of the project and feeder paths. Goldratt advocates using buffers that are one-half the total duration for the path they are intended to protect. The project buffer should be one half the length of the CC. The feeder buffer should be one half of the length of the feeder path.

3.2.1 Benefits of Goldratt’s Approach

This is extremely valuable for a number of reasons. First, when safety time is aggregated it can be significantly reduced and still provide a greater amount of protection. Actual task durations are nothing more than random numbers drawn from the distribution of possible outcomes. (I realize team members and management can affect this outcome, but for this argument’s purpose, that is not important.) If each resource wants to protect itself from a late finish, it will add buffer to the task estimate relative to the standard deviation for the distribution. For example, if the distributions are normal and the resource wants a 95% chance of finishing on time, it would need to add 1.65 times the standard deviation to its average task duration. Thus, the total buffer in the schedule would equal 1.65 times the additions of the individual standard deviations. If the team does not take advantage of early finishes, as has been argued is typical, the overall chance for the project finishing on time is still far less than 95%. If, on the other hand, safety times are aggregated, the standard deviation of the entire project is the square root of the sum of the squares of the individual standard deviations. This amount is far less than the sum of the individual standard deviations. Theoretically, for an actual 95% success rate the team would have to add 1.65 times this aggregated standard deviation to the sum of the individual average task completion times.

A second major advantage of aggregated buffers is that they encourage teamwork, which can lead to early task finishes. When the team shares an aggregated buffer and is primarily judged on overall project success, it promotes offloading non-essential tasks from constrained resources. It also encourages passing on early finishes so that the team can increase project buffer. In addition, this change promotes constructive peer pressure. When a team shares an aggregated buffer, they are much more dependent on each other for success and will "push back" against teammates who unnecessarily waste the buffer. When resources have their own safety time, they feel that it is theirs to use, even if it is not needed. When the safety time is community property, the dynamic is completely different.

A third advantage of buffers comes from how Goldratt uses them in conjunction with feeder paths. Typical project management software, such as Microsoft Project, encourages project managers to start all tasks as soon as possible to minimize the risk of a late finish. For non-critical path tasks, this equates to maximizing the amount of slack between the feeder path and the critical path. Because of the time value of money, and the fact that important new knowledge could be missed, it makes more sense to start all tasks as *late* as possible. During a project, particularly a product development, decisions are constantly being made and new information is continually being generated (for example, market information). There is measurable value in postponing tasks (particularly design tasks) to take advantage of as much of this new information as possible. Feeder buffers allow the project manager to compromise between the risk of delaying the CC and the value of delaying decisions and investments. They allow project managers to measure the risk they are taking and then track the progress as the feeder path is completed.

The last major advantage of buffers is that they can be used to manage a project through simple numerical measurements, which can be compared across projects. Analysis of buffer consumption allows project managers to focus their energies on the highest leverage tasks. This allows critical management time to be used more efficiently and helps to avoid demoralizing micro-management. Management is encouraged not to micro-manage by the "green" buffer management area and to manage only high leverage tasks. Buffers also provide a simple means for communication both within and between projects. This can provide a global metric and help managers to apply their limited resources on the tasks that will have the greatest impact on the moneymaking ability of the company.

3.2.2 Shortcomings of Goldratt's Approach

Managing a project through buffer analysis is something that Goldratt did not discuss in depth in his book. His partners introduced this enhancement to the ITT teams. The specifics of buffer management were never addressed, other than to explain that the project manager should divide the buffers into three zones and expect them to be consumed as the project progresses. Both Harris and ITT are presently dividing their buffers into three equal portions to define the red, yellow, and green (act, watch & plan, and OK) segments based on recommendations from the Goldratt associates. Buffer management is one area of CC that can use improvement.

3.2.3 Suggested Improvements

First, management should vary the percentages of buffer which fall into each segment using prior data from similar projects. If the project has a lot of uncertainty and as a result is deemed to be at a high risk of missing schedule, management should drive the actions of the team by increasing the percentage of buffer which falls into the act or watch & plan segments. Defining the red, yellow, and green zones of projects' buffers is one of the high leverage controls which CC gives to project managers and senior management because the zones of the buffers can motivate the team's actions.

The second enhancement managers can make to CC is in defining the absolute size of buffers. Goldratt recommends always using 50% of the path that is being protected. Thus, a project buffer should be 50% of the length of the CC; a feeder buffer should be 50% of the length of the feeder path. Although 50% is probably a good starting point, this percentage should vary from project to project, and even from task to task, as a proportion of the assessed standard deviation against which the buffers are protecting. This is another control point which managers can use to drive the actions of their teams. If a task or project is appraised to have very high schedule variability, managers should increase the amount of protection associated with it. This follows straight from statistical theory, the greater the variance of a distribution, the wider the range necessary to capture the same percentage of the outcomes.

Lucent Technologies has resources estimate the quickest a task could be done and the slowest it could possibly take in order to estimate each task's standard deviation. They then use a feature within ProChain which uses mean sum of squares (of these standard deviations) to calculate required buffer sizes. A less mathematical approach would be simply to alter the percentages ProChain uses to calculate buffers up or down depending on perceived variability and the need for protection. Ultimately, there is a tradeoff between the desired "precision" of the buffers and the amount of time necessary to calculate them. Although it would be comforting to use a formula to calculate optimum buffer sizes, no such formula exists. In the end, buffer sizes are just an estimation based on project manager experience and wisdom.

A third improvement project managers can make to CC is to monitor the rate of buffer consumption as opposed to the absolute size of the buffer. At this point, both Harris and ITT are keeping the size of their buffer's three zones constant as their projects progress. This is not appropriate. A project that is just weeks from completion should require a much smaller red zone than a project with a year to go. At a minimum, managers should assume a constant rate of buffer consumption as the project progresses. This would look like the solid line of Figure 16. A better approximation for most projects is shown in the dashed line. This is due to the difference between how far along a project team *perceives* they are and how far along they *actually* are.

At the start of most projects, mistakes are being made, but the team does not realize it because the rework has not yet been discovered. Thus, they will report they are farther along than they actually are. A project manager should expect little buffer to be consumed in the first portion of the project. Towards the middle of the project the rate of *discovering* unplanned iterations (rework) increases and one would expect the rate of buffer consumption to match it. This is also the stage at which the lengths of unplanned iterations are increasing (there is more that one can possibly have to redo).

At the end of most projects, the schedule risk is greatest. In one study by Cooper, the average project team was only half-way through the total time the project ended up taking at the point they estimated 90% of the work to be complete. [Cooper, 1994] The end of the project is also the timeframe when many different efforts of a project must come together. For a design team, this is the period when prototype parts are delivered and the team discovers whether the parts work together as planned. Lastly, this is the timeframe when the outputs of many projects are subjected to quality tests. These tests can often lead to the longest unplanned iteration cycles because they can lead to major redesign efforts. The dashed line of Figure 16 is the author's best estimation (with limited data) of average buffer consumption across projects. The plot is an exponential curve, and is driven by the rate of discovery and length of unplanned iteration cycles. This is an area which needs much more study and the historical buffer data of projects that used CC. Presently, managers should use historical data for similar projects to arrive at a similar estimation for each of their projects.

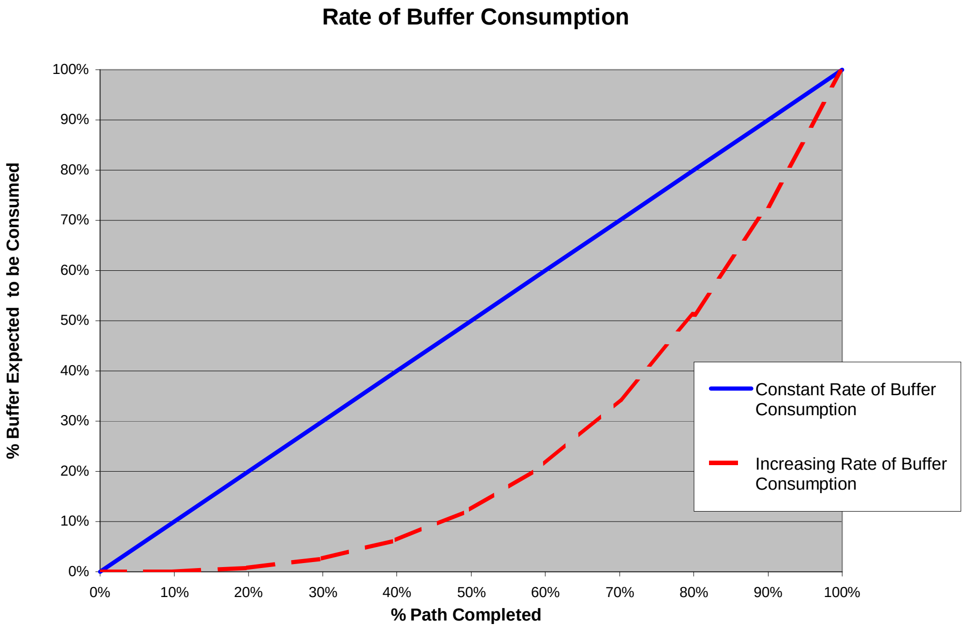

Figure 18: Expected Buffer Consumption

3.3 De-conflicting Resources

Another significant Goldratt change to the Critical Path methodology is the de-conflicting of constrained project resources. This feature is the most visible difference between a project's critical path and its critical chain. De-conflicted resources are the only change that drives the critical chain to be anything other than the critical path. Although this is already being done by many project managers in conjunction with CPM, Goldratt makes this an explicit part of using his methodology. Project managers at ITT had not been formally de-conflicting resources, particularly across projects.

3.3.1 Benefits of Goldratt’s Approach

De-conflicting resources within a project during the scheduling phase helps make the schedule more realistic by allowing us to assume no multi-tasking when making task time estimates. It also helps the team react to potential resource constraints proactively while changes can still be made to the schedule. Lastly, it can clarify exactly what the cost of resource constraints are to the company and help make a strong business case for adding resources during constrained periods.

When a company applies CC across all of their projects (termed multi-project by Goldratt), the greatest benefits of resource de-conflicting can be derived. At this higher level, the company can strategically decide which resource should be the constrained resource across all projects. This is very similar to strategically choosing which process step will be your bottleneck in a manufacturing setting, and then designing the rest of your plant around this step’s cycle time. All other process steps on average will have greater maximum capacity than your bottleneck; the bottleneck sets the pace for the entire plant and pulls work into the manufacturing line.

In a project environment, the variability is usually much higher than in a manufacturing environment, but the same theory still applies. Management can strategically choose which resources should, on average, be the constraint for the group. All other disciplines would have slightly more capacity than the “bottleneck” resource. When laying out CC schedules for an entire division or group, the bottleneck would be de-conflicted across all projects. When scheduling new work, management could look at the bottleneck’s Critical Chain timetable to estimate when they will have enough capacity to take on additional work. If used effectively, the bottleneck could act as the pacesetter (Goldratt calls this the “drumbeat”) for the entire division and would pull work into it. This would help to minimize excess work in progress (“design inventory”) which can slow all resources. By design, resources other than the constraint would have excess capacity and would thus have free time. This is a major paradigm shift because management has trained employees that in order to avoid layoffs, they must always appear to be busy. This is the reason employees do not acknowledge many tasks as having finished early.

When this same methodology was applied to the machinery in a factory setting, Goldratt claims that the average plant was able to increase its production 40% with no capital investments. [Newbold, 1998] Goldratt also contends that he expects to find at least that amount of untapped capacity within project teams.

3.4 Dealing with Suppliers

Goldratt recommends using CC to decide when to pay supplier expediting charges and when not to. In theory, suppliers have a queue of work to be done and will be willing to move higher margin work up in the queue.

3.4.1 Benefits of Goldratt’s Approach

CC can tremendously improve a corporation's relationship with its suppliers. If they collaborate with the supplier, as ITT did with the LCPS supplier and with Leica, the teams go through training together and work jointly to maintain buffers. Even if suppliers are not project partners, CC helps a company to become a better customer to its suppliers.

The CC network will enable a project team to tell its suppliers exactly what the impacts of delays are instead of always "crying wolf." When tasks are on the CC, the company can evaluate precisely what price they are willing to pay for expediting charges. When a task is not on the CC, the company can give its suppliers extra time to reduce charges. In either case, the communication is clear and business decisions are being made with data instead of gut feelings.

From the supplier's point of view, this is an improvement as well. If all customers demand their job be done as quickly as possible (as is typical), suppliers have no better method to schedule their work than first in, first out. If, on the other hand, CC enables customers to define their urgency more clearly, suppliers can segment their markets based on this urgency and charge higher premiums to customers who need their products more quickly. This is common in the package delivery industry. Theoretically, CC could create this more efficient market.

3.4.2 Shortcomings of Goldratt's Approach

There are many markets where the customer cannot pay for quicker service. Government contracting is an example. By law, government contractors cannot pay subcontractors higher fees for quicker service; the INOD team faced this problem when attempting to implement CC. This is a government driven market inefficiency. At best, applying Goldratt's principles with many suppliers will require educating them. Many suppliers offer a hard due date and will state that nothing can speed up delivery. Furthermore, culturally many business owners feel it is unethical to allow customers to pay to be placed at the front of a queue of other waiting customers.

3.4.3 Suggested Improvements

Goldratt fails to mention the option of collaborating with suppliers as ITT did. Collaborating accomplishes the task of educating suppliers and proved to be quite effective for both the INOD and LCPS teams. It also helps foster the teamwork necessary for shared buffer management to be successful.

Goldratt also fails to describe how to deal with supplier hard delivery dates. These are not an average duration; they are a contracted date. If they are treated conventionally, an additional 50% of their duration will be added to the schedule in the form of a buffer. It is recommended that schedule writers track these contracted durations separately and add little if any buffer for them (but also do not cut them by 50%).

3.5 Organization

The facilitators added many facets to the network building workshops that are not by definition part of CC, but proved to be very effective in managing the projects. Having the important members of the project team work jointly to put the project network together would have been powerful with or without CC. First, there was much more buy-in from the team since they took part in putting the schedule together. Second, the task estimates were more accurate because the resources who were closest to the work made their own duration predictions. Lastly, communication was improved during the project because the entire group knew what each other's responsibilities were and had the global picture of how the team's objectives would be accomplished. Of course, there is a limit to the effectiveness of this approach. Project teams with hundreds of geographically dispersed members could not effectively hold a network building workshop with the entire team present. The underlying principle still holds. The closer the responsibility of building the schedule is to the people who will be doing the work, the more exact the network and task estimates will be and the more buy-in management will receive from their team.

3.6 Goal Setting

Another facet that the facilitators added to CC was having the teams clearly define the success metrics (goals) for each project. Although this might seem like common sense, management would most likely have assumed each team member understood their projects' goals had it not been for the Goldratt consultants. Investing the time up front, as a team, to clearly delineate the project's long-term objectives must improve the odds for project success. If a team is not clear what their goals are, how can they hope to achieve them. The Goldratt partners have stated that it generally takes between four and twelve hours to obtain clear alignment on a project's goals, even given that teams generally start with a written mandate from management.

3.7 Network Building

Working backward to put together the project network was yet another facilitator enhancement. It seemed to be very potent in helping to break paradigms entrenched from previous project work. This tactic helped the team break their mental models from previous projects and differentiate between when finish-start constraints were necessary and when they were just nice to have.

Most importantly, the consultants were very good at employing commonly used project management techniques, such as breaking up large tasks in order to maximize task overlap. Their "outsider status" gave them objectivity that was advantageous when challenging assumptions and forcing paradigm shifts. Their relentless determination kept the workshops on track, even through all of the rather tedious details. At the same time they helped the team understand that no schedule or design would ever be perfect, and that it was important for team members to determine when work was "good enough."

3.8 Critical Chain Software

Although it is possible to manage a small CC project without dedicated software, it is far from optimum. The ProChain software greatly eased the workload of the schedule manager and increased the value of the schedule inputs to the team. The software enables all facets of the schedule to remain flexible, which is essential for the success of CC. Since the entire schedule is built on unbuffered task durations, and not due dates, when a task takes longer or shorter than was estimated, this shifts the start dates for all tasks downstream.

The software also allowed the schedule keeper to update the schedule more frequently. Microsoft Project is not designed to deal with buffers. Furthermore, many of Project's automatic features run counter to the CC philosophy (such as starting tasks as *late* as possible and de-conflicting resources). This forces the user to override the automatic features and rely on “must finish on constraints.” Frequent schedule updates seemed important for a successful implementation because they reinforced the team’s sense of urgency and helped ensure the project managers were making decisions with up to date data. With the individual task status reports in hand, it took the author less than 15 minutes to update an entire schedule. This left far more time for proactive buffer management and increased the team’s confidence in the CC outputs.

The software also prints out buffer summary reports and resource readiness alerts, which are useful for communication both to senior management and within the team. The software is extremely flexible. It will allow a project manager to alter the size of any buffer by changing the percentages being used for calculation or by manually entering a number of days. It will also allow the project manager to delete buffers and manually select the tasks that make up the CC. The software is fairly easy to learn and is inexpensive. However, it does need work on the multi-project implementation and in easing the generation of custom reports.

3.9 Intangible Benefits

ITT reaped a number of intangible benefits as a result of implementing CC. First, CC acted as a team building tool. The team goes through training together and then shares responsibility for preserving their buffers. If the incentives are aligned correctly, all team members will strive to help those working on CC tasks.

If implemented correctly, CC can improve employee morale. Most workers do not enjoy multi-tasking and would prefer to work on one task until it is complete. This was apparent on the INOD team when team members were clamoring to get their hands on the red pieces of chain. At the other extreme, employees also do not like feeling as if they have to stretch work in order to appear busy. If management truly makes the paradigm shifts CC calls for, non-constrained resources should expect to experience some slack time and should not be “punished” for it.

A second way CC can improve morale is to help minimize “fire fighting.” Many companies build no safety into their project schedules, but give employees an “incentive” to use their personal time as a buffer. As Newbold points out, “It is expected that projects will have ‘crunch times’ during which people will work extreme hours. Sometimes these crunch times last for months.” [Newbold, 1998] Short-term, this appears to be very attractive to the project manager inasmuch as it will both speed up the project and can lower costs since many employees are not compensated for their overtime. Long-term, this often leads to burnout and eventually the loss of valuable assets, namely employees. This can lead to lower current or future profitability. Unfortunately, many companies do not look that far ahead. [Newbold, 1998]

CC also clears up communications between team members, between project managers, and between project managers and their senior management. Team members know what to expect from each other and what global impact their local decisions have. They are also given a common vocabulary through the CC training. Project managers can better compare one project to another and use this data to assign resources equitably. Project managers can also clearly convey the state of their projects to senior management without having to give them more detail than necessary.

Lastly, CC can improve a company's bidding process. Resources give estimates for the average amount of work to be done instead of taking into account work they are doing on other projects. Overall, the estimates become much more meaningful and consistent. Using the same process repeatedly will allow a company to track actual task durations against estimates and learn from this data, both globally and locally.

3.10 Critical Chain Weaknesses

There are a few aspects of project management that CC does not sufficiently address. The first of these is the quality of the work done. Goldratt contends that project quality (similar to the scope of problems addressed) and project duration can be traded off against each other. Yet, he never specifically addresses how a project manager can ensure his team does not undermine quality goals in the rush to finish the project. Being the first to market is meaningless if the team brings the wrong product to market. This was one area that the Goldratt consultants did not specifically address, other than to exhort that the team had to learn when a task was "good enough."

There was an unspoken understanding among team members that quality was an understood imperative and would not be traded off for speed. Quality is not specifically addressed in other scheduling tools, such as CPM, either. CC does address "over-quality" because team members are expected to turn over work early if they feel they have met their personal quality objectives. Other methodologies give a resource little motivation to stop optimizing their work before the task deadline, and this can be wasted effort.

Cost is another area that CC does not explicitly address. On one hand, the Goldratt consultants postulated that project cost and duration could be traded against one another, but later they exhorted that a quicker project is usually a less expensive project. Other than that, cost was never addressed. Using CC does not rule out the use of standard Microsoft Project costing methods (input an hourly rate for each resource and multiply by the average task durations), but it is difficult to estimate a cost for the buffers. This became a problem with the INOD government contract. The government does not allow funding buffers, although on high variability projects this would probably make sense. ITT ended up using its traditional cost estimating methods for both INOD and LCPS.

Iterations are another area that CC does not properly address. The ITT teams handled planned design iterations by estimating the average number of expected iterations for a given block. We then modeled that many iterations within Microsoft Project by laying the tasks out repeatedly in a sequential manner. The average task duration was assigned to each sequential task. Although this method will not lead to the most accurate aggregate average duration, it did make it easier to track progress. Another weakness of this method is that it can lead to the schedule becoming a self-fulfilling prophecy. In order to avoid this problem, the team agreed that if fewer iterations were necessary than were expected, we would skip the extra tasks built into the network. If we had needed more iterations than planned for, the additional time would have had to come out of the buffers. Another method for dealing with planned iterations is to aggregate all tasks involved in the iteration into one "super-task" and then build this task into the network. The team can then use Eppinger's methodology to arrive at an accurate expected (average) time for the overall task. [Eppinger, Nukala, and Whitney, 1997] Although this method will lead to a more accurate time estimate, it makes it more difficult to track the progress of the project using the schedule.

No project management tools currently available effectively deal with unplanned iterations. At least CC gives the team buffers, which can be used to absorb most unplanned iterations. A reasonable length schedule will never have buffers long enough to handle major unplanned iterations. Management must use historical data to proportion the sizes of buffers to accommodate the amount of schedule risk they are willing to accept.

3.11 Summary

Overall, CC is a substantial improvement to the Critical Path method. The task estimates are more meaningful, aggregating buffer at the end of the project is a more efficient use of safety, and de-conflicting resources will lead to more predictable finishes and higher employee morale. Although, as addressed above, CC does not explicitly address quality, cost, or iterations, even in these areas it is a slight improvement over Critical Path. If the cultural issues, such as reengineering incentive systems, helping workers to avoid multi-tasking, and accepting slack time for non-constrained employees are properly addressed, CC will only serve to benefit a company.

4 Implementing Critical Chain

This chapter is written so that it can be used as a stand-alone CC implementation guide. The author has attempted to incorporate all of the lessons learned during the research of applying this new methodology. The chapter is written assuming the team will be working in Microsoft Project with the ProChain add-on.[3] There are obviously many project types the author was not exposed to because of the limited length and scope of this study. These recommendations are meant to be tempered with project manager wisdom and should be bolstered by referencing a more thorough CC text such as *Project Management in the Fast Lane, Applying the Theory of Constraints* by Rob Newbold, St. Lucie Press, 1998.

4.1 Getting Senior Management Buy-In

Critical Chain is not a methodology that can successfully be applied in a vacuum to a single project without senior management support. This is because most present incentive systems induce employees to act counter to what CC requires. Employees who build a project schedule with average task times are taking a leap of faith that management will change the metrics used to evaluate them. Project teams must also feel confident that management does not see their buffers as "padded" time. Buffers must be seen as a crucial component of the CC schedule. To ensure success, management must fully support CC and drive the cultural paradigm shifts.

If a group is attempting to sell CC to their management, many avenues can be taken. Persuading members of management to read one of the books written on CC is probably a good start. Compiling historical data on company project performance and contrasting it with data from companies presently using CC would most likely be very convincing as well. In the end, if the top management for a company or division cannot be convinced of CC's value, I would be hesitant in attempting to implement it. The cultural changes necessary for long-term success are so great that failure would almost be ensured. This would only serve to hurt the morale of the teams that attempted it, and inoculate the company against a future successful implementation if management's beliefs changed.

4.2 Single or Multi-Project Implementation

The first implementation decision is whether to apply CC to all projects simultaneously, or to apply it to one or two pilot projects to build support. There are strengths and weaknesses of both approaches. One of the strengths of picking just one or two pilot projects is that it simplifies training, which results in quicker accomplishment. When applying CC to pilot projects, as ITT did, only the pilot project team members, senior management, and other project managers need CC training. When implementing throughout an organization, the entire division must be trained before beginning the execution. Harris Semiconductor used the latter approach and began their training approximately six-months before ITT, but ended up starting their first CC projects after

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[3] For more information contact Creative Technologies at ProChain@compuserve.com or (203) 265-7590.

ITT was well into its pilot projects. It remains to be seen if this delay will be recouped as ITT works to spread CC to other projects.

The pilot project approach can also allow the company to cultivate a CC subject matter expert, who can be used to reduce the cost of training subsequent teams. Furthermore, this trainer can incorporate company specific lessons learned from the pilot projects into the training of future teams (such as ITT did with the use of resource readiness alerts, red and yellow chains, E-mail alerts, and reformatted project meeting agendas).

Another benefit of the pilot project approach is that it is simpler. This is because applying CC to multiple projects that share resources requires more complex deconfliction. A drawback with this approach is that some of the specifics of implementing CC are different between using CC in the single and multi-project environments. An example of this is that in the multi-project environment, Harris is not using resource readiness alerts. Instead, resource managers prioritize and assign resources' work daily. The reasoning is that globally it might make more sense to have a resource work on one project's feeder task if its feeder buffer is very low, even if the resource is supposed to be working on another project's CC task. Resource managers are tasked with optimizing across all of the projects using buffer analysis, and resource readiness alerts might limit their flexibility or confuse workers if priorities shift.

Since this research was primarily on a single-project implementation, the author does not have first-hand experience using CC in the multi-project environment. Thus, it is unknown how broad these discrepancies are, or how difficult the training from single to multi-project will be for employees. Since most companies will eventually desire to progress into the multi-project environment, this is an obvious area for further study.

The last, and possibly greatest, benefit of the pilot project approach is that it requires a smaller initial commitment from the company. This allows the successes of the pilot projects to increase support for CC and bolster arguments for future implementations. The risk of this approach is that employees can argue that the pilot projects' successes are due to the increased management attention they received and not due to CC. This effect was seen at ITT and is difficult to counter. Many employees are resistant to change and see pilot projects and new methodologies as "fads" which can be outlasted. On the other hand, if CC is applied to all projects simultaneously, it is hard to ignore management's commitment, and hope that the new tool will be short-lived or applied only to "other" employees' projects.

Despite the drawbacks, the author still recommends using the pilot project approach. The "across the board" approach can take years to show quantifiable improvements, which would require heroic management support and foresight to stay the course. It is also slower, which deprives the company of the benefits it could be receiving from quickly applying CC to its most crucial projects.

4.3 Dealing with Suppliers

The second major decision to be made is how to deal with project suppliers. Suppliers have the power to delay a project if not managed properly. If a supplier's outputs will be a major portion of the project (particularly if they fall on the CC), both teams should go through CC training and network building concurrently. This way both companies' teams will have a common background, which will allow them to work jointly to arrive at schedule solutions that are mutually beneficial.

If a supplier is a smaller part of the overall project schedule, CC should be used only to communicate more effectively with them. Once the CC network has been created, the purchasing department can use the schedule to determine needed due dates for supplier inputs. As stated earlier, this allows the purchasing department to determine exactly how critical each supplier's timeliness is to the project and compensate for expediting only where benefit in the CC is gained.

It is best if purchasing can persuade suppliers to estimate their average completion times for the team. They can then set up a payment plan that gives the supplier the incentive to finish as quickly as possible. If purchasing resorts to negotiating contract delivery times with suppliers, these should be treated differently than average duration estimates. Suppliers will not sign a contract in which 50% of the time they are late. Contract delivery times are already buffered by the supplier and require no further buffering within the schedule.

4.4 Training the Project Teams

Training the project teams is the most important aspect of implementing CC. Education, done appropriately, is a mechanism for employees to take ownership over the solution. People must understand what management is trying to do, how it affects them, and logically how it relates to the goals of the company. If they do not understand what management is trying to do or how it affects them they are less likely to do it. As Newbold points out, "If they don't understand how the solution relates to the goal for the organization, they will be less likely to contribute effectively to it. With proper education, people are more likely to agree that a concept really can become a solution to their problems." [Newbold, 1998]

The most credible and effective trainer is somebody who has successfully used CC on previous projects. At this point, there are at least three consulting firms that provide CC training. For the first few projects, using the services of one of these consulting firms is recommended. That should give the company enough time and experience with CC to develop its own CC trainer to support future CC projects.

The author recommends at least one full day of training on CC concepts for the senior management, key members of the pilot project team, and other project managers just before applying CC to the first project. This will allow time to cover all of the material and still work through some scheduling examples. An introduction to the multi-project environment would require an additional half-day. All team members should have at least a two-hour introduction to the CC vocabulary and concepts as this is about as quickly as this core material can adequately be covered.

Once the group has gone through the initial training, it is beneficial to have management periodically reinforce the concepts through mass distribution E-mails and refresher classes.

4.5 Putting Together the Project Network

Putting together the project network is the single most time consuming step when applying CC. It is important to first convince the project manager and team that it is worthwhile to invest time in planning their actions. As Newbold states, “Some managers feel that, since plans can never be ‘precise,’ there is little point in making them. When plans are made they are frequently treated as unimportant or even irrelevant.” [Newbold, 1998] A project plan can be one of the team’s best means of communication. It can help the project manager deal with inherent project uncertainty and aid in making decisions. A good project plan can help the entire team to be more productive. “You don’t need to walk as slowly when the lights are on.” [Newbold, 1998]

Putting together the project network should include the following steps:

1. Clearly state the objectives of the project and of the project plan.
2. Working backward in time, determine the needs to be met and the tasks required to meet them.
3. Determine the logical relationships between tasks and needs.
4. Estimate the resource requirements, task durations, and costs.
5. Calculate the Critical Chain schedule, including buffers.
6. Evaluate the plan according to budget and timing restrictions.
7. If necessary, go back to an earlier step and revise the plan. [Newbold, 1998]

4.5.1 Building the Task Network

This is the most important step when applying CC. This methodology is dependent on having a good project network that the project manager and team feel properly models the approach they will take to successfully complete the project. Since putting together the project network can be time consuming, it is very important to have all of the stakeholders present so that they feel a sense of ownership in the plan. This will also help to avoid having to revise the schedule after the workshop, as the INOD team had to do.

It is also crucial that all members understand the goals of the project. The goal for a project team is similar to a Mission Statement with technical context and specifications. The objective of the LCPS team was agreed to be when ITT and K and M are in full production with “a design that meets ITT’s cost and K and M’s profit objectives; comparable if not better quality and yield for both ITT and K and M; and the ability to make weekly shipments.” Whatever amount of time this step requires will be well worth the investment. Once the goal has been drafted, construct the project network working backward from this point.

The author recommends building the network within Microsoft Project in the PERT format as the team progresses. If the schedule is first entered into project in the Gantt format, the PERT format will be unusable later because Project does not lay out the PERT cells in a logical workflow pattern. There are readily available Project software add-ons which improve the functionality of Project when working in the PERT view.[4] If the team has access to a video projector, display the network as it is entered so that

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[4] For more information contact Critical Tools at (512) 342-2322 or www.criticaltools.com

everyone can follow the development. Alternatively, the network can be documented on paper large enough that the entire team can easily view it. Decide at each juncture what tasks must be completed before being able to start the current task. This method helps the team to identify just the unavoidable predecessor-successor relationships. In this fashion work backward through the entire schedule until all tasks and task dependencies have been identified.

Work to break tasks into a fine enough detail to allow the maximum amount of task overlap. Deal with necessary iterations by having the team guess the average number of expected iterations needed, then serially insert that number of iterations into the network. Avoid milestones if possible, as these tend to lead to sub-optimization because they force the team to spread their project buffer throughout the schedule.

4.5.2 Assigning Resources

Once the task network is complete, the team must assign specific resources to each task. This should be done as a team in order to clarify roles as the work is completed. Identify the minimum number of people necessary to complete each task. When possible avoid assigning percentages of resources. This is for two reasons. First, assigning percentages is counter to the spirit of CC as it encourages multi-tasking. Second, it complicates troubleshooting the schedule once ProChain has leveled the workload and identified the CC. If a task requires less than 10% of a resource's time, the resource is not worth capturing, and considered merely a consultant to the task.

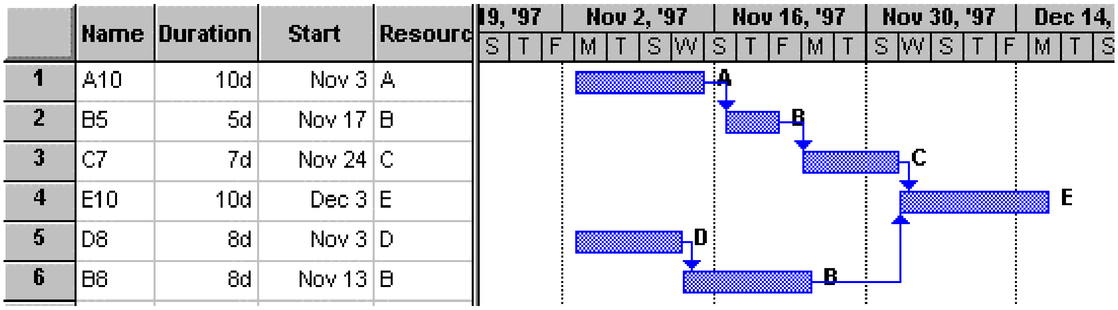
Discourage the team from repeatedly assigning the same resources to multiple tasks, as this will force ProChain to extend the schedule during the resource deconfliction step. For example, although the systems engineer needs to participate in all facets of a design to ensure proper systems interfaces (the interfaces between mating parts or components, typically designed by different engineers), avoid assigning him or her as a partial resource in all design tasks. Instead, break out "identifying systems interfaces" as separate tasks and assign the relevant groups to these smaller tasks.

4.5.3 Assigning Task Times

This is the first step that differs from building the project network for any other methodology. At this point, it is probably worth reviewing the theory behind CC with the team. Reinforce that the CC tasks times are average task durations and thus, it is expected that 50% of the tasks will finish "late." Also, emphasize that team members should anticipate having all necessary inputs and resources before starting work on a task. Lastly, the team should give average estimates for working on the given task non-stop (no multi-tasking). Using these guidelines, have the team, as a group, give an estimate for each task. Peer pressure can work in the team's favor to drive all safety from the task estimates. The team will "push back" against an estimate that appears padded, but no individual should feel attacked because the pressure is equally distributed. Work through the entire schedule until the team arrives at reasonable average durations for all tasks.

4.6 Working with ProChain

Since the ProChain software played such a critical role in the successful implementation of CC at ITT, this section will be quite detailed. At this point, the project network is complete and the CC can be identified. This can be a very quick step if the team has entered the schedule into the PERT format of Project as it was working. Figure 19 shows an example project network in the Gantt view, which will be used throughout this section.



	Name	Duration	Start	Resourc
1	A10	10d	Nov 3	A
2	B5	5d	Nov 17	B
3	C7	7d	Nov 24	C
4	E10	10d	Dec 3	E
5	D8	8d	Nov 3	D
6	B8	8d	Nov 13	B

Figure 19: Gantt View of Example Network (same example as was used in Section 1.3.2)

Save the final network before using any ProChain options. In general, it is a good practice to use numerous file saves under different names when working with Project because it has many automatic features which cannot be "undone" and can destroy a schedule. The author will only be discussing single project use of ProChain.

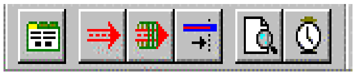
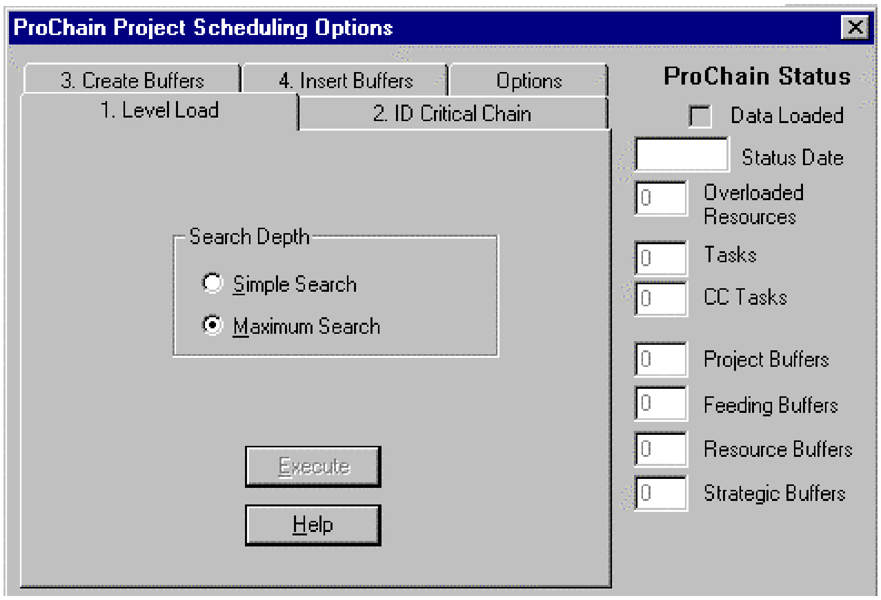


Figure 20: ProChain Toolbar

Toggle the "ProChain Options" icon on the ProChain toolbar, which looks like an index card (farthest to the left). This will bring up the "ProChain Project Scheduling Options" menu box (Figure 21).



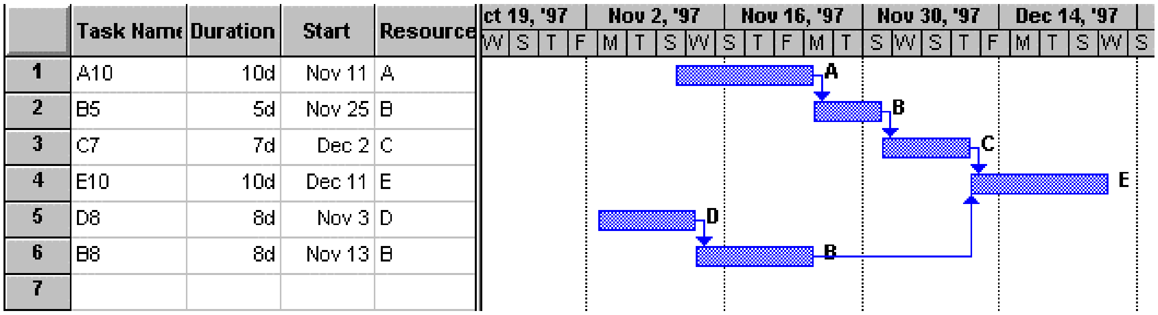
ProChain Project Scheduling Options

Search Depth
○ Simple Search
● Maximum Search

ProChain Status
☐ Data Loaded
Status Date
0 Overloaded Resources
0 Tasks
0 CC Tasks
0 Project Buffers
0 Feeding Buffers
0 Resource Buffers
0 Strategic Buffers

Figure 21: ProChain Project Scheduling Options

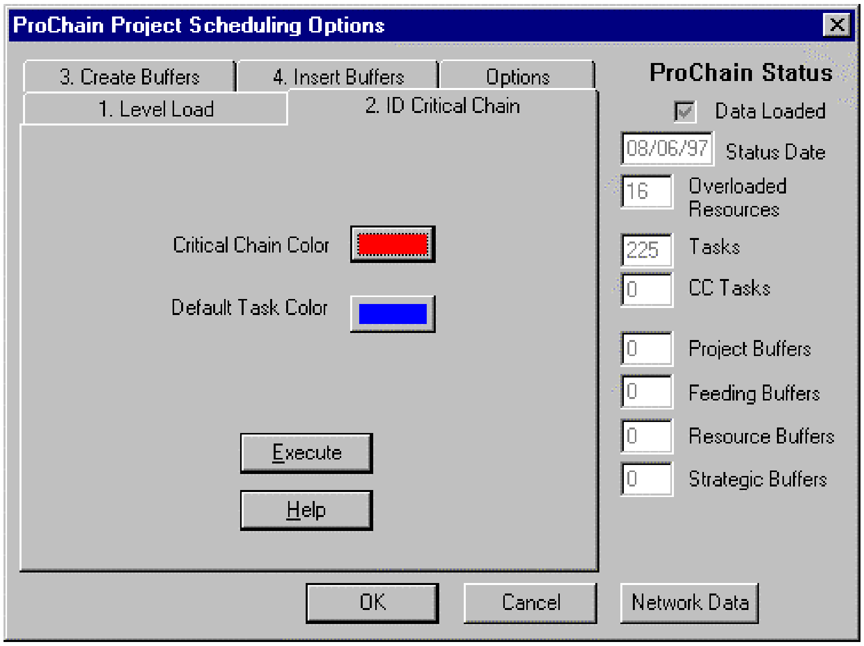
First de-conflict resources by depressing the "1. Level Load" tab, "Maximum Search," and "Execute." At this point, closely examine the network in the Gantt format to ensure that only tasks with actual resource conflicts were displaced.



	Task Name	Duration	Start	Resource
1	A10	10d	Nov 11	A
2	B5	5d	Nov 25	B
3	C7	7d	Dec 2	C
4	E10	10d	Dec 11	E
5	D8	8d	Nov 3	D
6	B8	8d	Nov 13	B
7				

Figure 22: Example Schedule After De-Conflicting Resources

The next step is to toggle the “2. ID Critical Chain” tab and “Execute.” Again, ensure that the software arrived at the expected outcome. If the project manager wishes to alter the CC manually, this can be easily accomplished using the “Toggle CC Task” icon, which is a red arrow pointing to the right (see Figure 20). At this point, the team should work to shorten the CC by rethinking its finish-start constraints, adding resources to CC tasks, or reexamining CC task durations. After each iteration, re-level the workload, recalculate the CC, and work to shorten the new CC.



ProChain Project Scheduling Options

Critical Chain Color 🟥

Default Task Color 🟦

ProChain Status

☑ Data Loaded

08/06/97 Status Date

16 Overloaded Resources

225 Tasks

0 CC Tasks

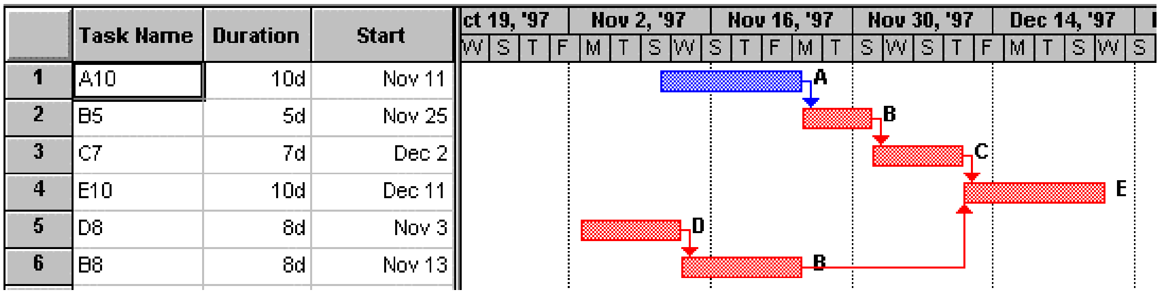
0 Project Buffers

0 Feeding Buffers

0 Resource Buffers

0 Strategic Buffers

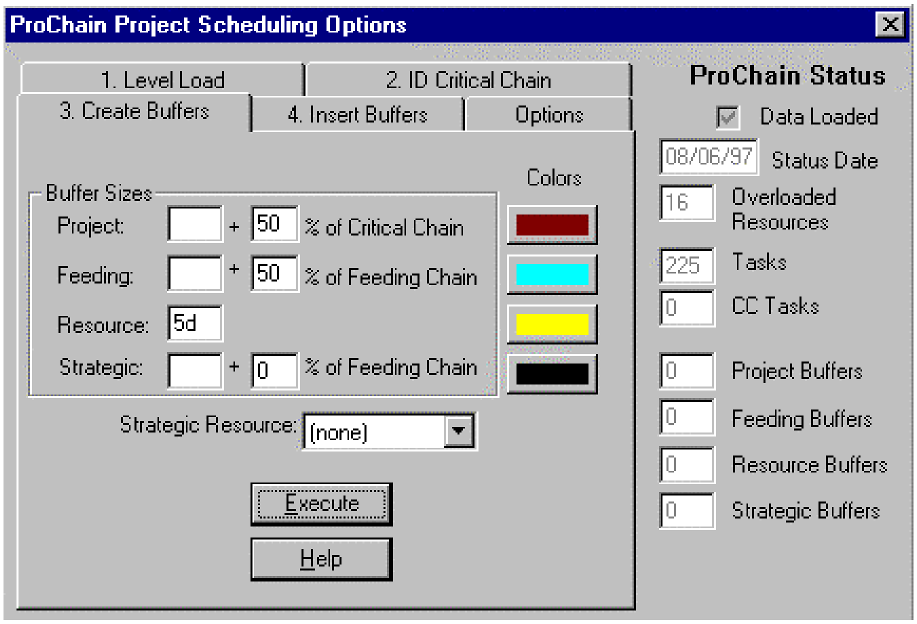
Figure 23: ID Critical Chain Dialog Box



	Task Name	Duration	Start
1	A10	10d	Nov 11
2	B5	5d	Nov 25
3	C7	7d	Dec 2
4	E10	10d	Dec 11
5	D8	8d	Nov 3
6	B8	8d	Nov 13

Figure 24: Sample Schedule with Critical Chain Identified

Once the team is comfortable with the CC, toggle the “3. Create Buffers” tab. The size of the project, feeder, and resource (readiness alerts) buffers can all be customized by entering a fixed number of buffer days and/or changing the percentages used. The default is the Goldratt recommended 50% of the path being protected for the project and feeder buffers and five days for the resource buffers.



ProChain Project Scheduling Options

Buffer Sizes

Project: + 50 % of Critical Chain

Feeding: + 50 % of Feeding Chain

Resource: 5d

Strategic: + 0 % of Feeding Chain

Strategic Resource: (none)

ProChain Status

☑ Data Loaded

08/06/97 Status Date

16 Overloaded Resources

225 Tasks

0 CC Tasks

0 Project Buffers

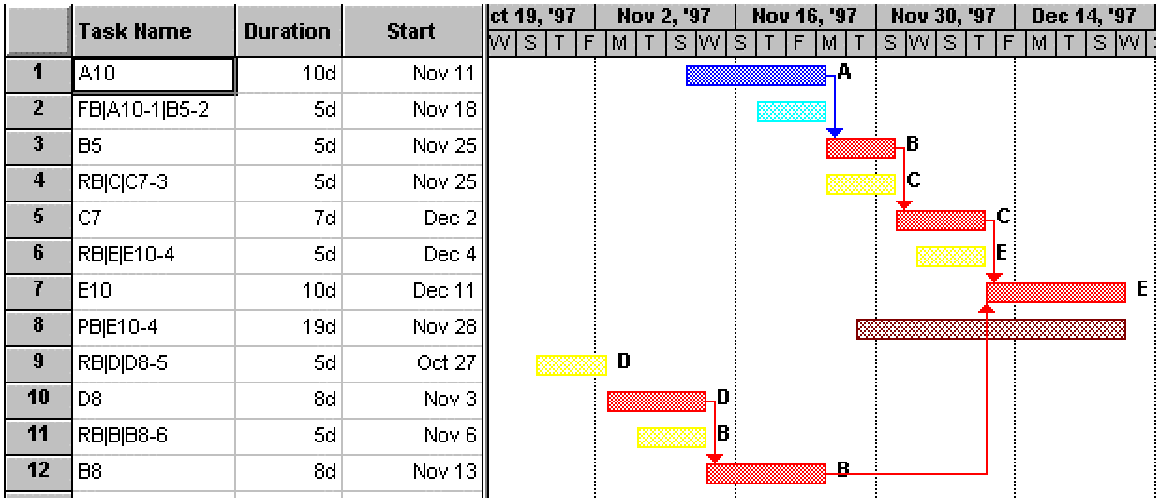
0 Feeding Buffers

0 Resource Buffers

0 Strategic Buffers

Figure 25: Create Buffers Dialog Box

This will create all of the buffers, but not insert them. In the Gantt view, the buffers will be new numbered tasks with the assigned color (see Figure 25) for the Gantt bar and a title with the corresponding “PB…”, “FB…", or “RB…” (see Figure 26). It is recommended that an organization standardize the selected buffer colors so that project managers and team members can easily understand other teams’ schedules. I have chosen to make project buffers rust colored, feeder buffers light blue, and resource buffers yellow. In the PERT view, all buffers will be stacked on top of each other in a corner so that they do not obstruct the project network.



	Task Name	Duration	Start
1	A10	10d	Nov 11
2	FB|A10-1|B5-2	5d	Nov 18
3	B5	5d	Nov 25
4	RB|C|C7-3	5d	Nov 25
5	C7	7d	Dec 2
6	RB|E|E10-4	5d	Dec 4
7	E10	10d	Dec 11
8	PB|E10-4	19d	Nov 28
9	RB|D|D8-5	5d	Oct 27
10	D8	8d	Nov 3
11	RB|B|B8-6	5d	Nov 6
12	B8	8d	Nov 13

Figure 26: Example Schedule with Buffers Created

The next step is to insert the buffers. In some cases, there will not be enough slack in the schedule to insert the full feeder buffer. For example, if there are two parallel paths, one 20 days long and the other 16 days long, the 20-day path would be on the CC and the 16-day path would require a feeder buffer (see Figure 27). The Goldratt recommended feeder buffer would be eight days, but since there are only four days slack, this does not leave enough room to insert the full buffer.

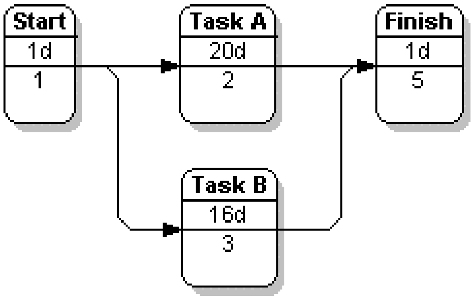
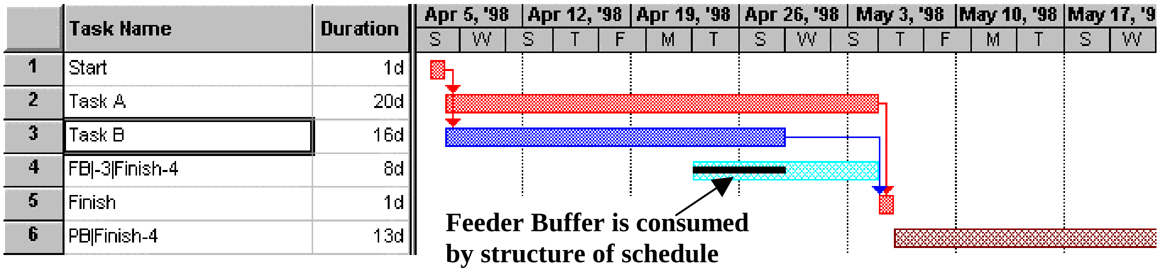


Figure 27: PERT View of Buffer Insertion Example

The project manager has two options. The first is to create a four-day break in the CC and insert the full buffer. This will lengthen the schedule by four days, but will yield a more predictable finish date because the project buffer is only protecting the CC path. The second option is to insert only four days of the feeder buffer, and treat the other four recommended days of the buffer as having been consumed by the structure of the schedule. This will produce a shorter schedule. However, since the feeder path does not have the recommended amount of buffer, there is a higher probability that a late finish of the 16-day path will delay the CC. Thus, the project buffer is now absorbing some of the non-CC path risk and the finish date is less certain. The Gantt view of this option is shown in Figure 28.

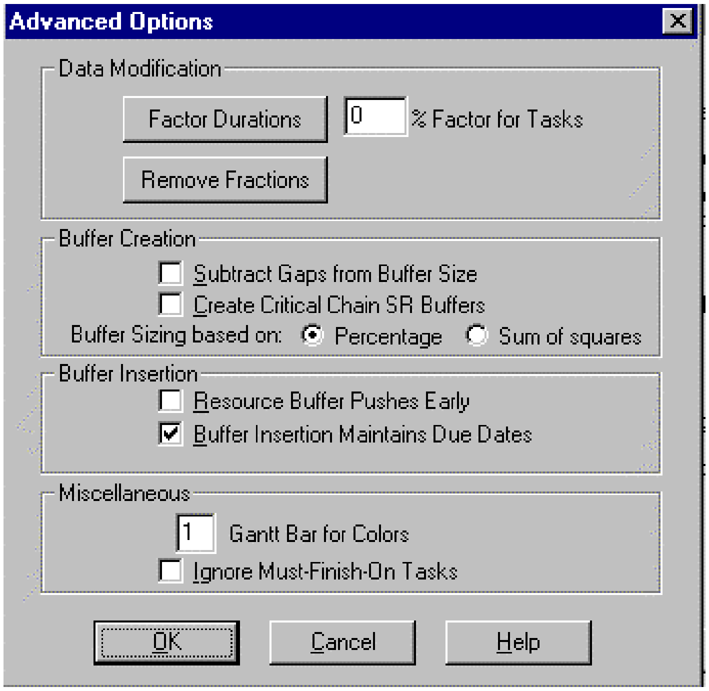


	Task Name	Duration
1	Start	1d
2	Task A	20d
3	Task B	16d
4	FB|-3|Finish-4	8d
5	Finish	1d
6	PB|Finish-4	13d

Feeder Buffer is consumed by structure of schedule

Figure 28: Project Gantt View of New Example with Full Feeder Buffer Not Inserted

To have partial feeder buffers inserted so that the CC is not extended, first toggle “Options” on the “ProChain Project Scheduling Options” dialog box. Next toggle “Advanced,” this will open the dialog box shown below in Figure 29.



Advanced Options

Data Modification
0 % Factor for Tasks

Buffer Creation
☐ Subtract Gaps from Buffer Size
☐ Create Critical Chain SR Buffers
Buffer Sizing based on: ● Percentage ○ Sum of squares

Buffer Insertion
☐ Resource Buffer Pushes Early
☑ Buffer Insertion Maintains Due Dates

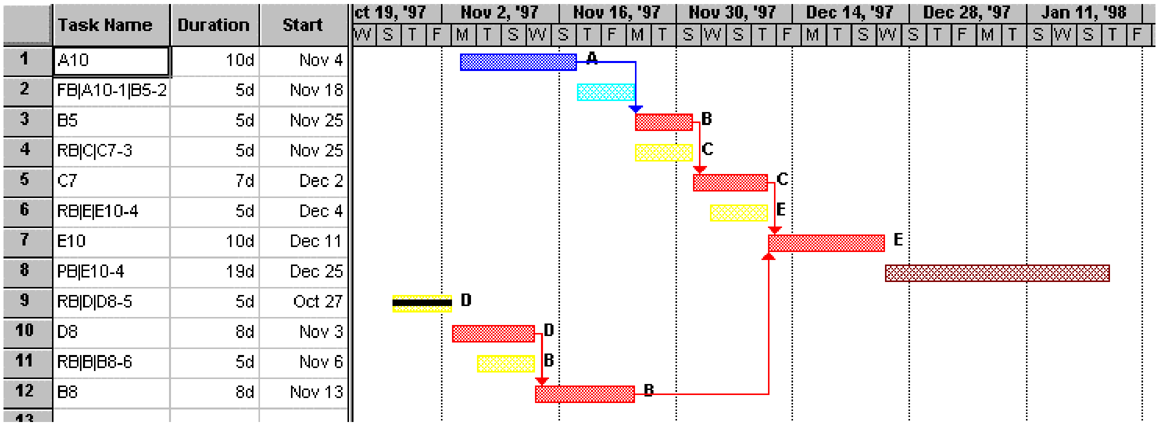
Miscellaneous
1 Gantt Bar for Colors
☐ Ignore Must-Finish-On Tasks

Figure 29: ProChain Advanced Options Dialog Box

Put a check mark as shown in the box labeled “Buffer Insertion Maintains Due Dates.” One software glitch with this option is that after inserting the buffers the project buffer must be repositioned so that it begins at the completion of the last task (it will be shown **finishing** at the completion of the last task and having been completely consumed).

The author chose to insert partial feeder buffers (second option) instead of inserting breaks into the CC for all three ITT projects because the highest priority for all of the projects was to finish as quickly as possible. This also seems more appropriate according to the underlying CC theory. Inserting a break in a project’s CC is similar to taking a rest in the middle of the “relay race.” If predictability of the finish date is the highest priority (such as when timing an expensive marketing campaign), the first option described might be more appropriate.

In either case, the final step is to insert the buffers. This is accomplished by toggling “4. Insert Buffers” and “Execute.” The Critical Chain schedule is now complete and should be examined to ensure that the schedule correctly mirrors the strategy that the team and project manager have chosen. Notice that in Figure 30, D’s resource buffer has a dark line through it. This is because the present date for this schedule was November 3, so this buffer has been completely consumed (D needs to start work today).

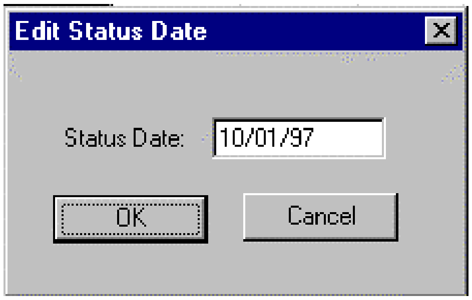


	Task Name	Duration	Start
1	A10	10d	Nov 4
2	FB|A10-1|B5-2	5d	Nov 18
3	B5	5d	Nov 25
4	RB|C|C7-3	5d	Nov 25
5	C7	7d	Dec 2
6	RB|E|E10-4	5d	Dec 4
7	E10	10d	Dec 11
8	PB|E10-4	19d	Dec 25
9	RB|D|D8-5	5d	Oct 27
10	D8	8d	Nov 3
11	RB|B|B8-6	5d	Nov 6
12	B8	8d	Nov 13

Figure 30 Original Example Schedule with Buffers Inserted

4.7 Maintaining the Schedule

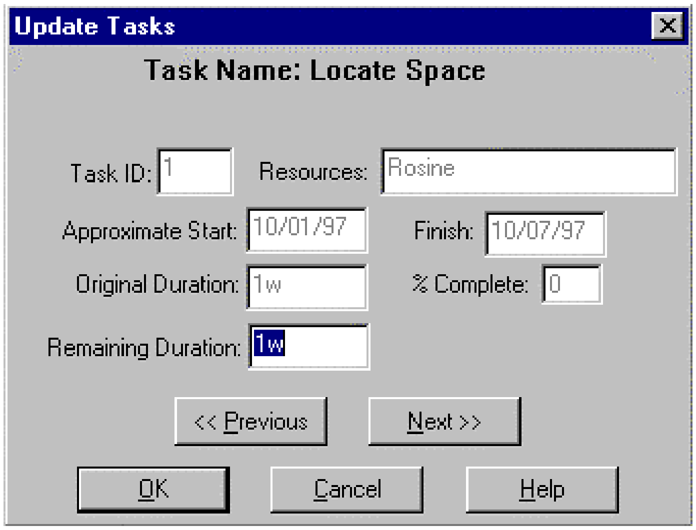
Maintaining the CC schedule with ProChain is quite simple. The first task is to get status reports from all resources working on tasks. The resources should estimate the average number of days the task they are working on will take to finish. Since the task reports are given in remaining duration, all reports must be received at the same time. Although this might seem difficult to accomplish, it can be simple if resources get in the habit of sending status reports at prescribed intervals. The author recommends three updates per week for most projects. Once all of the reports have been collected, click on the “Update Tasks” ProChain icon, which looks like a Gantt bar with an arrow (see Figure 20). This will open a dialog box that will first ask for the present date (see Figure 31).



Status Date: 10/01/97

Figure 31: Status Date Dialog Box

ProChain will next step through all tasks which could possibly be worked on and allow the user to update the remaining duration of each (see Figure 32). A successor task will not be displayed if its predecessor has not been entered as having zero days remaining.



Task Name: Locate Space

Task ID: 1
Resources: Rosine
Approximate Start: 10/01/97
Finish: 10/07/97
Original Duration: 1w
% Complete: 0
Remaining Duration: 1w

Figure 32: Update Task Dialog Box

When all tasks have been updated, ProChain will update the entire schedule by calculating the status of all buffers. Resource readiness alerts can easily be communicated through the use of the "Resource Buffers" icon, which looks like a clock (see Figure 20). This report will list the status of all resource buffers and can be given to team members to warn them when they have less than five days until commencing work on a CC task. The "Buffer Report" icon, which has a piece of paper and magnifying glass (see Figure 20), will list all of the feeder buffers and the project buffers in descending order of percentage consumed. It also lists for each buffer the task that is most likely consuming the buffer. Thus, senior management can use this report by starting at the top and working down towards the less consumed buffers. This will pinpoint the high leverage project tasks on which to concentrate their energies.

4.8 Special Cases

Unfortunately, the time constraints of this research did not permit applying CC to longer or more complex projects. The author has no reason to believe that the CC methodology will not readily scale up for larger projects, but further research is necessary to validate this.

4.8.1 Long Duration Projects

For multi-year projects, it is probable that the members of the team will not remain fixed for the life of the project. Other than requiring the persistent training of new team members, this should make applying CC even more desirable because CC's primary benefit is that it clarifies communication. On long projects with rotating team members, clear communication is essential. Another benefit of using CC is that it is a standard process improvement across projects. This should help facilitate the transferring of team members between long-lasting projects seamlessly.

Another characteristic of longer projects is that team members often are clearer about near-term tasks than those towards the end of the project. This can lead to pushing all of the project schedule risk to the end of the project by optimistically estimating later tasks. CC should help prevent this if the network is put together as recommended in this paper. If all significant resources take part in putting together the network, the size of the project buffer should correctly track the schedule risk of the project at any stage. To deal with the later tasks' uncertainty, the team should define short-term tasks in greater detail and define later tasks in blocks with only enough detail to correctly determine the CC. This will enable the team to define a nearer term "hard point" on the schedule, which the CC will have to pass through. Once the team has identified this point, they can work backwards from it as if it were their final objective. The INOD team knew that delivering the first six prototypes to the government would fall on the CC. In order to make the network building task more manageable, the team chose to work backward from this point and defined tasks after this point in very generic blocks.

Periodically (every other quarter) the team should hold shorter network building workshops to further define the approaching tasks. This way the team will always define the short-term schedule with enough detail to take advantage of all the benefits CC affords.

After each network building workshop, the team should recalculate the CC to ensure it is still accurate. It is recommended that the new project buffer be inserted using the original finish date of the project. In other words, the project buffer will absorb the variance in the length of the CC after the rebaselining, and the project should always end on the same date. This complies with the underlying CC theory and will prevent the team from having to explain to management why the finish date of the project shifts each time the schedule is rebaselined. This approach was used for both INOD and the facility expansion. Both of these projects have multiple phases and are expected to last approximately three years. In each case, the project goal was written as a metric for long-term success, but the networks depicted primarily the first phases of the projects. The later phases were depicted only in very rough terms. The teams have had subsequent shorter network building workshops to further define the next phases of the projects.

4.8.2 Large, Complex Projects

Large, complex multi-site projects should also benefit from the clearer communication CC affords. The author's opinion is that the larger and more complex the project, the more the team would benefit from applying CC. However, training a larger team and achieving the necessary paradigm shifts across different organizations is much more difficult.

The same recommendations made for long projects apply to large, complex projects. In addition, since getting all resources together for a large network building workshop would not be manageable, the senior leadership should break down the project into chunks that are more manageable. These chunks can then be broken down into more detail in network building workshops by the local teams. Once the CC's for each of the segments has been determined, combining all of the data within Project should be trivial. This will yield an overall CC for the entire project. The task update reports could also be collected and entered at the local level. A password protected web site could easily be generated, which would allow each resource to input their updates into the schedule. The same web site could also be used to communicate the outputs from the CC schedule to the team.

4.9 Cultural Keys to Successful Implementation

Tell me how you measure me and I will tell you how I will behave.

Dr. Eli Goldratt

As mentioned earlier, CC is more than just a new project management methodology. CC requires a cultural change in the way projects and people are managed. If an organization undertakes implementing CC without changing the metrics that are motivating their employees to act the way they are, they are predestined to failure.

Employees who are punished for late task finishes will not honestly estimate average task durations in the future. An employee who works non-stop on a task yet still finishes late should be praised by the project manager and the team. On the other hand, a team member on the critical chain who finishes early despite student syndrome and multi-tasking should be reproached (unless management forced the multi-tasking). Of course, the quality of an employee's work should remain a constant metric.

Teams must be evaluated as a unit as well. This will help to nurture the necessary teamwork and motivate team members to act for the global good. Some teams at ITT are awarded project bonuses as a unit. This does not prevent superior individuals from standing out, but will lessen the non-value-added competition among team members. To avoid sub-optimization management must support CC by monitoring overall project completion and not individual task or milestone completions.

Another cultural key to success is enhanced management communication with **all** team members, particularly articulation having to due with priorities and the allocation of resources. CC will provide data to enable smarter decisions. As an example, the impact of pulling key resources from a project for 30 days to work on an important proposal can be credibly assessed and the value weighed against that of capturing the new business. No matter what path is chosen, management must communicate the rationale for the decision, or the teams will get the wrong message.

Management must also ensure that company policies do not promote jumping to a new task until the first is complete (multi-tasking). Instead, incentives should be aligned so that employees have the data to prioritize their work and then work through their assigned tasks in that sequence. This requires intense coordination between managers, especially in matrix organizations. Training all stakeholders and then communicating CC schedules throughout the organization should help to accomplish this responsibility.

Obviously most of these cultural changes cannot take place without impassioned change agents at the top of the organization. The support needs to be resolute and constantly reinforced to persuade those averse to change that the changes cannot be outlasted.

5 Conclusions

5.1 Areas for Further Study

This work leaves three significant directions open for further study (listed in the priority the author advocates they be pursued).

5.1.1 Multi-Project Implementations

The first area for further study is implementing CC in the multi-project environment. This paper has shown that CC can be quite effective when applied to individual projects that do not share resources. Much greater improvements in resource utilization efficiency should be possible if the TOC can effectively be applied to an organization with shared resources across multiple projects. Presently there are different beliefs among the different lead users and CC practitioners as to how best to implement CC across multiple projects. Thus, within multi-project CC there are two directions for further study. First, one could attempt to determine what is the best methodology for implementing multi-project CC. Second, one could try to quantify the benefits of the multi-project implementation, if any. Unfortunately, these will both be difficult topics to effectively study.

Before attempting to quantify multi-project results, it makes sense first to ascertain which methodology being used represents the best practice. This should be accomplished by benchmarking the lead users of CC against each other as they perfect their multi-project implementations.

The next area of study should attempt to qualify and quantify the multi-project improvements. This will be very difficult to accomplish because most likely there will not be a suitable “control sample” for the research. The next best alternative would be to benchmark successful lead implementers of multi-project CC against both their own historical performance and against the performance of non-CC users within their industry. Choosing an industry with rapid product development, such as the semiconductor industry, should help to gather adequate data quickly (Harris Semiconductor or Lucent Technologies would be obvious choices for further study).

5.1.2 Larger, More Complex Projects

A second direction for further implementation study is with larger and more complex projects. The author sees no reason why most of the methodologies used at ITT will not scale up with larger projects; nevertheless, this area should be researched. Ideally, one could implement CC on an extremely large complex project, such as the design of a new automobile platform or aircraft. Obviously, projects of this magnitude take years to complete, but enough data would be available to make preliminary conclusions after the team had been trained, put together the first project network, and used buffer management for a few months. Ideally, a researcher could continue to track the progress of the project through completion and continue to provide lessons learned.

5.1.3 Buffer Consumption Rates

A last area for further study is analyzing buffer consumption rates and recommending improved methods for buffer management. This will vary from project to project and industry to industry, but best practices will certainly emerge. Again, an industry with very short product life cycles should be investigated to maximize the amount of data collected. It is recommended that buffer consumption rates (both feeder and project) versus time are studied for numerous projects. The trends could then be identified and recommendations for improved proactive buffer management techniques could be advocated.

5.2 Conclusions

Critical Chain is a new project management tool that shows promise in single project applications. The average normalized finish for the two pilot projects at ITT Night Vision was .98, while the average finish for the ten non-CC projects benchmarked was 1.35. Although this difference is not statistically significantly, it does appear CC helped to improve schedule performance. The theories should extend to larger projects and to a multi-project environment, but additional research is necessary to validate this. Critical Chain appears to increase the morale and efficiency of resources and helps to minimize schedule risk and minimize project duration- a win-win situation.

The author has presented this research to numerous industry audiences. An overwhelming majority of the project managers have concurred with the behaviors Goldratt is attempting to address and agree in theory that CC should be an improved method for scheduling and managing their projects. Nevertheless, in many audiences there have been one or two project managers who have felt that CC won’t work for their particular projects. As a conclusion, some of these frequently given responses as to why CC will not work in a particular setting will be discussed:

The project I am managing is research and development, you can’t schedule creativity.

This is more of an argument against all scheduling techniques, not specifically CC, but it still warrants discussion. A schedule will be the project’s plan, which, if executed according to the plan, should achieve the objectives of the project. The intent of a project plan is to help advance and/or communicate understanding of the project. Plans are created to assist in decision making both before and during project execution. [Newbold, 1998] Without a schedule, it is very difficult to communicate the project strategy to the team and it is difficult to manage the project proactively. Without a schedule, management will have no way to determine when a project is not meeting expectations and should be terminated. Generally, R&D task estimates will have a wider distribution than more defined tasks, but this only means that the buffers will have to reflect this higher variability. Using average task estimates when dealing with higher variability tasks should be more advantageous because the weaknesses of buffering each estimate are even more pronounced than when tasks have tighter distributions.

Resources on my project work on tasks in teams, not as individuals.

This was also the case on many of the INOD and LCPS tasks. The ProChain software works just as well no matter how many people are assigned to each task. The only potential drawback to working on tasks in teams is that it can prolong the schedule if employees are on a number of different teams simultaneously. This is because the software will level the load for each team member individually so that a team-oriented task will not be scheduled to be worked on unless all team members are available. This correctly models reality if the entire team is actually needed; it is much harder to schedule a meeting for a large group than it is for a small group. This feature should enable project managers to pinpoint the constrained employees across all of their teams and use this data to optimize the makeup of their teams.

My project is too large and complex for this to be effective.

The larger and more complex a project, the more important it is that communication is clear. The stakes on large projects are higher and the room for improvement greater. The methodologies described in Section 4.8 should allow a project manager to scale up the methodologies successfully used at ITT.

My projects are too small for this to be worth it.

If an organization undertakes many small projects, their learning from applying the same methodology across all of their projects will be accelerated. CC can help to standardize their project scheduling and management and help to facilitate the formation of new project teams. The benefits from de-conflicting resources across many projects and identifying the resource constraint in order to minimize work in progress should also be more effectual in an organization with many small projects.

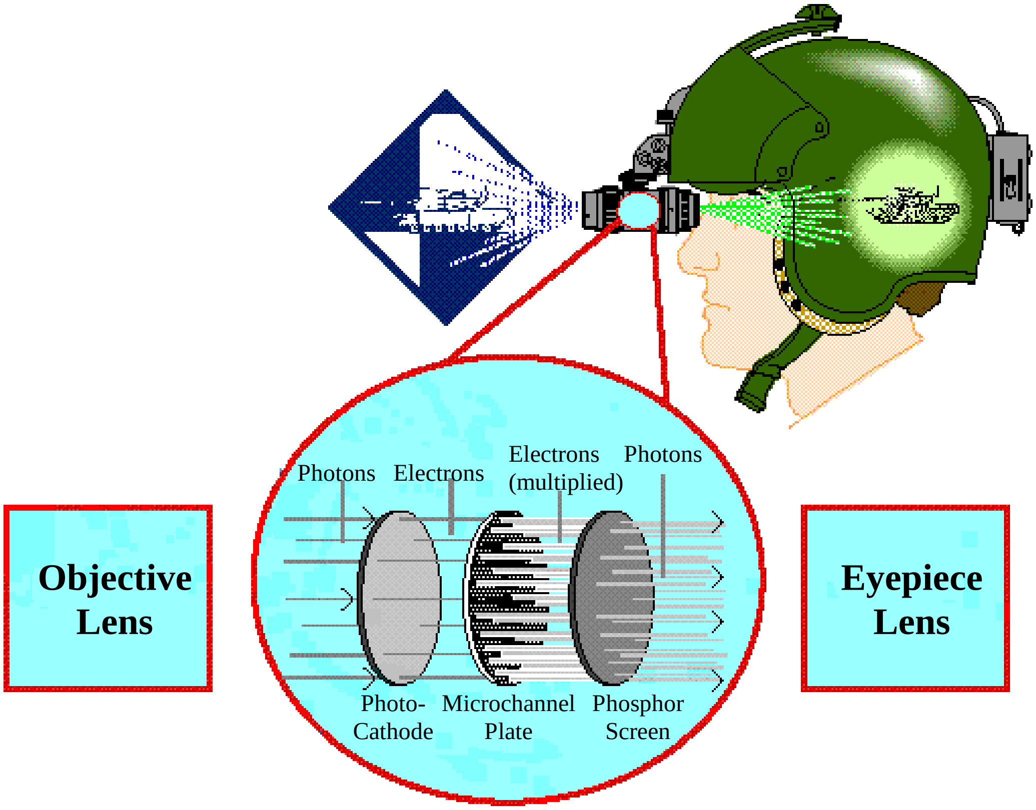
My teams don’t build any safety time into their task estimates.

If a company’s teams currently do not build any safety time into their task estimates, than 50% of the estimates must be finishing late. If early finishes are not effectively capitalized on, this would lead to dismal project schedule performance. In this case adding measured buffers should help to make project finishes more predictable. More than likely it is the case that the company culture is such that resources do not “admit” when tasks are completed early and management is interpreting this to mean that task estimates are unbuffered. Employees are very good at proving Parkinson’s law which states, “Work expands so as to fill the time available for its completion.” [Parkinson, 1957] In this case applying CC should help to change the culture and lead to dramatic improvements in project performance.

Task times are not probabilistic, I just need to get my team to give me the correct estimate.

A priori, task times are highly probabilistic; obviously once the task is complete there is a “right” answer for how long it took. Employees can be trained to better estimate a task’s possible distribution, but cannot be “trained” to give the “right” time estimates anymore than a gambler can be trained to pick the “right” horse.

Appendix A



ITT's night vision products are high-quality electro-optical systems that combine state-of-the-art technology and precision components in rugged user-friendly viewers. The heart of the system is an image intensifier that receives very minute amounts of visible light and near-infrared waves from the moon, stars, and night sky and amplifies them thousands of times. The principle used is called photoemission, which was first discovered by Heinrich Hertz in 1887 and theoretically explained by Albert Einstein in 1905. Photoemission is the release of electrons from a solid material as a result of energy put into the material by radiation and light.

The objective lens collects light that you cannot see with your naked eye and focuses it on the image intensifier. Inside the image intensifier a photocathode absorbs this light energy and converts it into electrons. These electrons are then drawn toward a phosphor screen but first pass through a microchannel plate that multiplies them thousands of times. The microchannel plate is a metal coated glass disk that multiplies electrons produced by the photocathode. These devices normally have anywhere from two to six million glass holes (or channels) in them, placed at a slight angle to the incoming light. Electrons entering a channel strike the wall and knock off additional electrons, which in turn knock off more, producing a cascading effect. When this highly intensified electron image strikes the phosphor screen, it causes the screen to emit light that you can see. Since the phosphor screen emits this light in exactly the same pattern and degrees of intensity as the light that is collected by the objective lens, the bright nighttime image you see in the eyepieces corresponds precisely to the outside scene you are viewing.

Appendix B

Memo from ITT Night Vision General Manager to all employees (E-mail distribution)

Subject: Implementation of “Critical Chain” Project Management

This past summer, we began implementation of the “Critical Chain” approach to project management as a means of continuing to improve our ability to complete projects on schedule, within budget, and without decreasing scope. This approach is based on Goldratt’s Theory of Constraints and requires focused resource management for all activities on the critical chain of a given project. The critical chain is defined as “the longest path of dependent activities, given consideration of resources needed to perform the work.” Work begins on a critical chain activity when all necessary inputs to perform that work are available (such as equipment, data, prior analysis, and people) and continues uninterrupted until completion. The work is managed in this manner so that the overall duration of a project can remain as short as possible while providing a buffer against uncertainty - something that is always a given on a development project!

We have implemented this approach on three strategic projects at Night Vision: INOD weapon sight, low cost power supply, and our facilities expansion project. In 1998, we intend to implement this approach on all new development projects. Clearly, I believe very strongly that this approach will improve the overall performance of our company. To be successful, we need to work together to achieve this.

To clearly communicate who is on the critical chain of a project, we are implementing a physical system of red chains and yellow chains. The chain will be placed at the entry of the work site for an individual, indicating the following status:

Yellow Chain -This person is closely approaching critical chain status (within five days). This is a readiness indicator or “warning sign” that this person will soon not be available for non-critical chain work or discussions. Use these final days to coordinate any open issues with this person. (The chain will include an indicator of how many days remain until critical, or red, status is reached.)

Red Chain -This person is currently on the critical chain. It is essential that this person continue his/her project work uninterrupted. If you need anything from this person, speak to his or her manager and clearly communicate the urgency and scope of your need; the manager will coordinate alternate work arrangements, if possible.

If you have any questions on the Critical Chain methodology or the status of our pilot programs, please contact Phil Foster (facilities expansion project) or Steve Cook (INOD weapon sight and Low Cost Power Supply projects).

Appendix C

INOD Schedule

- Critical Chain resources are wor

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