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DRIVING COST REDUCTION AND CARBON PLANT PRODUCTIVITY IMPROVEMENT THROUGH THEORY OF CONSTRAINTS AND PLANNED MAINTENANCE CAPABILITY

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Abstract

Theory of Constraints (TOC) is a management approach that gives clear context for decision-making and can lead to lower cost and more efficient Smelter operations. TOC avoids local (sub) optimization and ensures that actions are aligned with "end-to-end" process performance. When a Smelter TOC operating strategy is cascaded down to the Carbon Plant, and then to the Paste Plant, it provides context for how to best approach Paste Plant operating and maintenance activities. In addition to defining the most appropriate strategy, TOC principles and tools can be applied to activities such as routine maintenance and larger non-routine maintenance projects. For example, Critical Chain Project Management (CCPM) is a TOC technique that increases the speed and quality of these activities and can increase asset reliability and available run time, giving lower cost production runs and greater predictability. This paper describes the cascading of TOC thinking and strategies down through a Smelter, leading to an example of how CCPM can be applied to a Carbon Plant maintenance project.

Theory of Constraints

Theory of Constraints (TOC) was developed by Dr. Eliyahu Goldratt during the early 80's, and introduced through his novel "The Goal" [1]. Goldratt used scientific methods to explain why factories commonly fail to achieve their targets, especially throughput. His findings clearly demonstrate that process **variability** (process outputs varying over time) and **dependency** (relationships between a process step and the steps that come before or after – a result of system design) conspire to drive chaotic process performance, specifically cost and throughput. Goldratt's insight, described as the "physics of factory flow", leads to the conclusion that *"the throughput of a system is determined by only a few critical factors, these being the constraints of the production system"* [2].

Understanding the constraint in a system enables Business Leaders to address the interaction between process variation and dependency so they don't create chaos. Theory of Constraints also provides a clear focus for variation reduction and the strategic use of capacity and inventory to manage and improve system performance. Knowing the system constraint enables Leaders to define operating strategies that reflect the different roles that process steps play in the context of the system as whole (e.g. constraint or non-constraint). When this is overlooked, the approach often becomes "improving all processes will lead to improvement of the whole." Goldratt was able to clearly demonstrate that this is not true, and improvement of individual process steps in isolation of the others with which they are dependent will actually degrade system performance.

TOC Implementation delivers benefits including a clear focus on:

- Where improvement will increase system throughput.
- Where improvement will reduce system costs.
- How and where to use "protective" production capacity (process step capacity > system constraint capacity) and buffers (i.e. inventory) to mitigate the effects of variation.

This clarity and focus can eliminate the production losses and waste in people and capital that occurs when organizations mistakenly strive to squeeze every bit of productivity out of every step in the process.

Implementation of TOC

TOC is applied through several specific management tactics:

1. Find and Exploit the Constraint. The performance of the system constraint is determined not only by its own capability, *but is significantly impacted by the performance of the other steps in the process.* When there is a clearly specified constraint, the strategy is to maximize the performance of the constraint (and therefore the overall system) - an "exploit" strategy can be defined, along with how other process steps must work to "subordinate" to the constraint (subordinate is to operate in a way that works to maximize the performance of the constraint).
2. Protect the Constraint. Protective capacity "unbalances" the system – a necessity if constraint throughput is to be maximized. This requires: a specific approach to activities that deliver capacity, such as maintenance and reliability, to ensure "reliable" protective capacity, signals that indicate when the protective capacity is not sufficient, and a plan for when and how protective capacity will be used.
3. Strategic Buffer Management. Strategically positioned and sized inventory buffers are used to mitigate the effects of variation (planned and unplanned) thereby protecting the constraint. This requires a strategy for how the buffer is to be maintained and used, as well as signals that indicate when the buffer is insufficient to protect the constraint.
4. Focused Variation Reduction. Variation reduction efforts are primarily focused in two areas – within the constraint, and upstream (flowing into) of the constraint. As variation is reduced, the need for protective capacity and inventory is lessened and flow is improved, resulting in increased throughput at lower cost. This increase in throughput is produced at the marginal incremental cost.

The strategic use of buffers according to TOC can be seen at times as in conflict with Lean Manufacturing principles (often noted for inventory reduction). This is not the case. TOC provides a scientific approach to establishing appropriate inventories to protect and maximize flow through the system. It defines what buffers are required and a means of specifying the protection provided by the buffers. Through efforts to reduce variation, TOC provides a clear set of actions that will lead to less reliance on buffers and hence reduce cost.

Implementing TOC in a Smelter Carbon Plant

Smelters are generally a serial dependent system that exhibits variation that can flow downstream (Carbon to Potrooms, Potrooms to Casthouse) or upstream (Potrooms to Carbon, Casthouse to Potrooms) and disrupt the overall process, leading to lost production and higher costs. Theory of Constraints starts with developing a site operating strategy, in which the Smelter constraint is identified, the roles of other major process steps are defined, and strategic buffers and management plans set.

The site strategy sets out the "role relationships" between major process steps in the system (Figure 1). As the system **constraint**, the Potrooms "exploit" strategy is focused on tactics for **maximizing** performance to maximize production. As it is in a **subordinate** role, the Carbon Plant will focus on **never starving** anode supply or **never disrupting** the Potrooms anode setting pattern, and producing anodes of a quality that will help to maximize the performance of Potrooms. The Casthouse, also in a **subordinate** role, will operate to **never block or slow** the flow of metal from Potrooms and **never "waste" production** from the constraint, as this is "unrecoverable loss." Both the Carbon Plant and Casthouse focus on **reducing cost** – not just locally, but on reducing entire system costs. These role relationships are then cascaded down to within the Carbon Plant, and the operating strategies for anode production steps are defined in a similar manner: identifying the throughput limiting step (called the control point) and how the other process steps will be operated to subordinate to this control point (Figure 2). Buffers and protective capacity plans are also developed at this level.

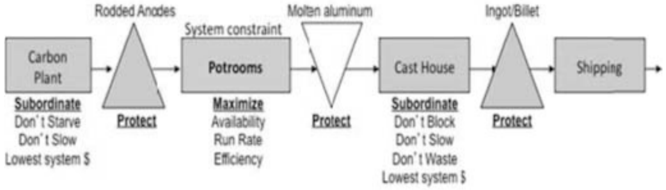


Figure 1. Role relationships between major Smelter processes.

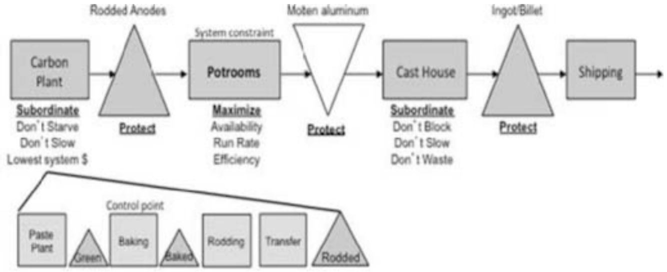


Figure 2. TOC strategy is cascaded down within the Smelter to the Carbon Plant, i.e. from site to department level.

As the Smelter operating strategy is cascaded down to the Carbon Plant, the first step is to identify what is limiting production (throughput). Each department will have a process step that regulates production, even if it is not the system constraint. In the Carbon Plant, this was identified as Anode Baking. The rate of production of the baking process is then tied directly to maintaining the buffer in front of the Potrooms (i.e. rodded anode stocks). The other process steps (Paste Plant and Rodding) are subordinated, they protect the performance of Anode Baking (i.e. seen as having capacity > anode baking).

The work of cascading TOC within the Carbon Plant continues within each area: Paste Plant, Anode Baking and Rodding Room. The principle of serial dependent systems subject to variation holds, regardless of the level at which the analysis is being done. Within the Paste Plant, it is determined that the Vibroformer is the "control point" (Figure 3). An exploit strategy is then defined to "synchronize" (in this case, maximize may not be the objective) the productivity of the Vibroformer to the buffer management plan for green anode stocks in front of Anode Baking (Carbon Plant control point). The Vibroformer is the focal point for Paste Plant throughput – it is operated to maintain the target green anode inventory. The other steps in the Paste Plant are operated to subordinate to Vibroformer operations.

Figure 3. Process flow sheet for the Paste Plant showing Vibroforming as the control point.

In the case shown in Figure 3, Vibroformer run time is a key part of exploit tactics, putting the focus on the planning and execution of planned maintenance repairs as a key driver of throughput - less time for maintenance shuts means more run time at the control point. The cascading implementation of TOC continues to give the visual strategy as shown in Figure 4.

Cascading TOC operating strategies delivers focus and clarity:

- It enables Leaders to know where to work and what to work on to lift system throughput and where to work and what to work on to reduce costs. Through clarity and focus, TOC drives chaos and reactiveness out of daily operations.
- TOC stops the waste of effort and resources "trying to get the most out of every process and reduce costs across the board." The Leader now has a clear view on where to best use resources to increase throughput and reduce costs.
- TOC drives the creation of properly designed measures that focus on throughput (and cost control) at the constraint and on "protection" in other areas through protective capacity and buffer management. It also provides a basis for analyzing daily performance and the "health" of the system.
- TOC provides a scientific and systematic means to reduce reliance on excess capacity and inventory.
- TOC focuses efforts to remove variation from processes where it will do the most good for the overall system.

Applying TOC: Critical Chain Project Management

Planned maintenance repairs are serial dependent processes that exhibit variation, with the "control point" in a planned repair being identified as the work "execution" step. This leads to a parallel application of TOC - an approach to project planning and execution called Critical Chain Project Management (CCPM). This is the application of the Theory of Constraints to the management of projects, including capital projects, major (or even routine) planned maintenance shutdowns, improvement projects, and so on.

If not managed, variation and dependency in a production process leads to reduced system production, (= lost revenue and higher cost). In projects, variation and dependency result in projects taking longer than planned, project work not being completed, or higher than expected project costs. In Figure 5, TOC applied in production is compared to a project setting.

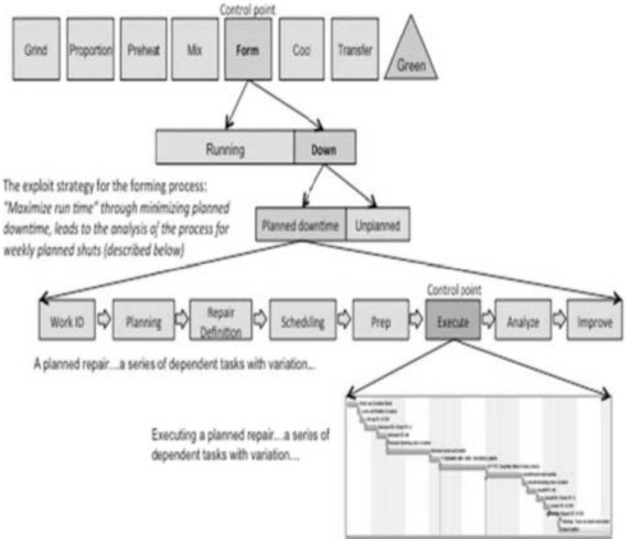
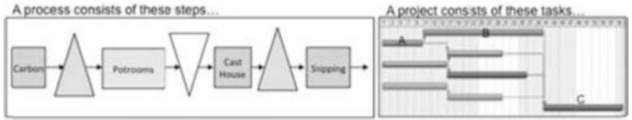


Figure 4. A visually cascaded strategy for the Paste Plant



	Production Process	Equipment Repair Process
The GOAL	Generate revenue through production (at requisite quality) leading to profit, now and in the future	Generate revenue through on time completion of repair with all tasks complete (at requisite quality)
Variation	Daily production	Task duration
Dependency	Carbon effects Potrooms, Potrooms effect Carbon..	A effects B effects C, B effects A,...
Inventory (Buffer)	WIP	Time
Protective Capacity	Non-constraint capability to "outrun" the constraint	Resource scheduling and slack time in the system
CONSTRAINT	Potrooms	***"THE CRITICAL CHAIN"***

Figure 5. A comparison of TOC in a production environment (left), and for a project, i.e. CCPM (right).

The thinking processes in CCPM applied to a project or a planned equipment shutdown are:

1. Focus on the constraint - All project tasks are not equally important. The "critical chain" (longest chain of dependent events after resource conflicts are removed), defines the work stream that will determine the overall project duration. Focusing on the critical chain ensures that the most important tasks in the project are done first.
2. Protect the constraint – Work outside the critical chain is set up as "feeder streams" and managed (with time buffers) to ensure they subordinate to the critical chain and are a pool of resources if action is needed to protect the critical chain.
3. Buffer management - A project "time buffer" is established to protect the project and the customer.
4. Variation reduction – Improvement can be focused on exploiting the constraint – either by reducing task times or compressing the critical chain.

Data show [3] that as many as 45% of major planned repairs do not finish on schedule, and that up to 50% of planned repairs cost more than 150% of the estimate. Remembering that a major planned repair is a project to be executed, the basic construct of such a repair can be described as shown below.

A major repair is a set of tasks that need to be completed – represented as "bars" on a Gantt chart. The tasks are not all independent – some need to be completed before others can be started, i.e. the lines connecting task bars as shown in Figure 6.

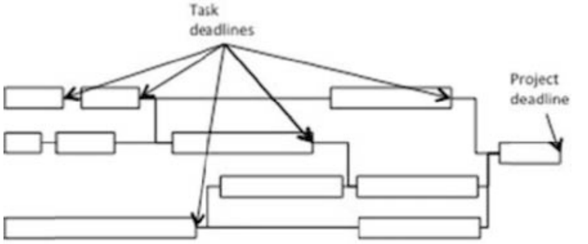


Figure 6. Major repair Gantt chart showing dependencies between tasks and intermediate task deadlines.

The Customer (Production Department) typically only wants to know about one deadline – when can the plant be restarted? To establish this, intermediate deadlines are set as shown in Figure 6. When every task hits its deadline, it is assumed that the repair will be completed on time, however this rarely occurs.

To improve the delivery of planned maintenance shuts, the way they are planned and executed needs to change including: the way task times are set, the way resource conflicts are resolved, and how safety time is added to protect against uncertainty. Further, a clear focus (critical chain) must be established to ensure planned repairs are fully executed and completed on time at the lowest cost.

A conventional approach to major repair planning can result in:

1. Safety built into in every task - to meet targets: To ensure that all deadlines are met, and remembering that individuals are held accountable for achieving these intermediate deadlines, safety (or "fat") is built into every task in the plan, "just in case."
2. Safety built into in every task - late starts: When every task includes safety, they do not always start on time; often they are started after an arbitrary delay as "there is a bit of room to move here". This is the "student syndrome" - waiting until the last minute to start an essay and then working endlessly (higher cost) trying to hit the deadline (potentially longer project duration).
3. Safety built into in every task – no early finishes: When every task includes safety, it is common for the task to extend for as long as is planned, or if a task is finished earlier than planned, the next task is not ready to start until the planned completion time of the previous task. Time ahead of plan is lost (Higher cost and longer duration).
4. The domino effect: Late task completion leads to a late start and so on; eventually these delays accumulate until the equipment repair either finishes late, additional resources are added to finish on time, or work is not done to end on time (Higher cost, longer duration, lower quality).
5. Embedded waste - historical standards: Improvement in equipment repair delivery can be limited because standard task time estimates may not relate to the actual work being done. Waste becomes built in to future standards, resulting in continual degradation as time estimates absorb this embedded waste (Longer duration and higher cost).
6. Embedded waste - "multi-tasking": Flipping resources between tasks when trying to hit intermediate deadlines

makes the critical path almost meaningless; it depends on which tasks are being worked on at the time, and how work is assigned. Progress cannot be rationally assessed, so it is not known which tasks are behind schedule and need attention, or if there are tasks ahead of schedule from which resources can be drawn to "recover" delays to keep the major equipment repair on plan. Multi-tasking has been shown to reduce repair productivity (cost, duration and quality are all negatively impacted).

So, what should the Leader responsible for major equipment repairs do differently?

a. Manage the entire project (global versus local).
b. Establish clear priorities focusing on the constraint.
c. Adopt a relay race mentality in planning and execution.

Global View of the Repair. CCPM is an approach that focuses on the whole project, and not just the tasks. Individual task deadlines are removed and safety is taken out of tasks without risk to the overall project – a project buffer is managed to protect the project, not the individual tasks. This involves several fundamental changes from conventional project (and major equipment repair) planning and execution:

1. Task durations are set differently.
2. Plan resource conflicts are resolved to avoid multi-tasking.
3. "Safety" is redefined and the way it is used is changed to protect the major equipment repair.

These will be demonstrated using a project plan with a series of dependent tasks with an estimated duration of 70 hrs. (Figure 7).

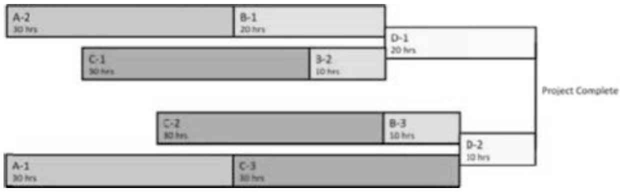


Figure 7. Conventional project plan, showing dependent tasks and a duration of 70 hours.

Setting Task Duration Estimates. Task duration is often planned using a single point (standard) estimate, and as discussed, these estimates often include hidden "safety" to ensure individual task deadlines are met. CCPM recognizes that there will be variation in task times and uses this to estimate task duration. Tasks are estimated based on historical task duration distributions at the 50th percentile ("most likely"). This means that not all tasks will be completed by the estimated time – a principle of CCPM critical to its success. Using task A-2 from the project plan shown in Figure 7, historical data gives the distribution of task times shown in Figure 8.

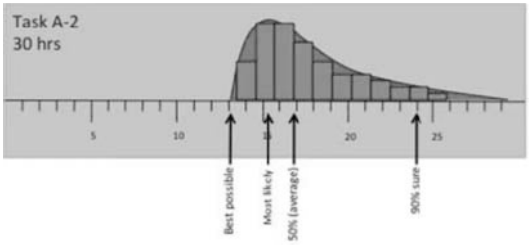


Figure 8. The historical actual distribution of A-2 task duration.

Using only "most likely" time estimates for all of the tasks, the project plan is reconfigured, giving a new project timeline with an estimated duration of 35 hours as shown in Figure 9.

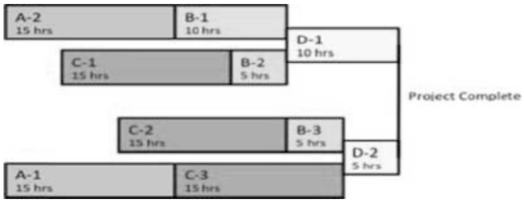


Figure 9. Project plan based on most likely task times resulting in a duration of 35 hours.

Resolve Resource Conflicts. The project plan (Figure 9) shows a number of resource conflicts to be addressed. The letters in Figure 9 represent tasks performed by the same resource group. When tasks are planned at the same time to be done by the same resource, this represents a resource conflict that leads to multi-tasking. Starting at the end of the schedule and working left, the tasks are shifted to resolve resource conflicts (Figure 10).

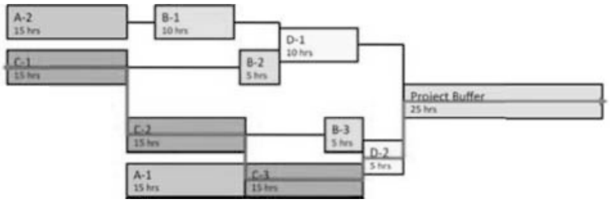


Figure 10. Project plan with resource conflicts removed (no multi-tasking), project buffer added, and critical chain identified.

After resolving resource conflicts, the critical chain (longest chain of uninterrupted events as indicated by the red line on Figure 10) is identified and a project buffer added. This buffer is derived from a "pooled risk" estimate using the tails of the time distributions for the tasks in the critical chain. The project buffer protects the overall major equipment repair and hence the Customer. With the critical chain established, the project buffer indicates a repair duration ranging from 50 to 75 hours; with 62 hours being the most likely (midpoint) finish time. Unlike in the initial plan (Figure 7), the resource conflicts have been resolved, which would have likely created chaos and lead to cost overruns or longer repair duration.

Feeder time buffers are added to the other chains of work, and shifted to an early start plan. Start times are added to each chain and the "safest" end time shown (Figure 11). For example, task G-2 is a feeder to G-4 (Part of the critical chain) and needs a time buffer. This makes the start of G-2 earlier and requires that the new resource conflict with A-2 is resolved, so task A-2 now starts earlier as well.

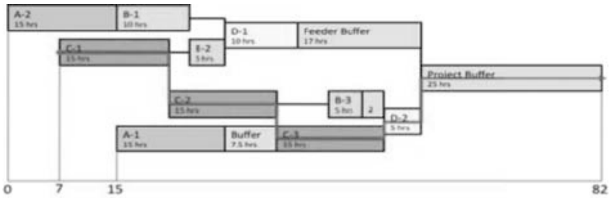


Figure 11. Critical chain with resource conflicts removed and early starts established.

Monitor project progress. Buffers are set up and "fever charts" developed for each project chain. Fever charts track consumption of the project buffer as tasks in the critical chain are completed (Figure 12). It signals (i.e. warns) if project completion within the projected window of time is at risk. The zones on a fever chart reflect the likelihood of the repair finishing in the high-end of the buffer (yellow mid-band) or exceeding the maximum buffer finish time (red upper band).

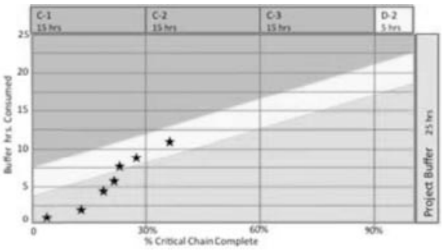


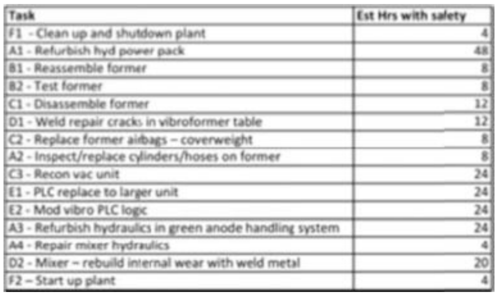
Figure 12. Example of a project fever chart

Project progress is reviewed using fever charts on a defined schedule: the buffers are analyzed, their status defined, and action taken as needed to protect the project. The use of fever charts to show the degree of buffer consumption (project and feeder), keeps the focus on the critical chain to protect the outcome. Actions are based on fever chart status, green (lower band), yellow, or red, i.e. if buffer consumption as a function of critical chain task completion is green, no action is required. If yellow, initial planning for action is needed - feeder buffers are evaluated as potential sources of resources and other resource actions considered. If red, action to "recover" the critical chain is required. Resources can be reassigned or added -examine feeder stream fever charts, which are ahead, which are behind? Can feeder stream resources be shifted to the critical chain – at no risk to the project? If not, what other resource actions can be taken to protect the critical chain? What is the pre-specified response plan?

The application of CCPM to project management and specifically to planned equipment repairs has an envious track record. Data from various industries shows that the duration of repairs can be reduced by as much as 30%. Recent experience of one of the Authors (KAS) with two major planned repairs has shown a reduction in repair duration of 50-60% [4].

Carbon Plant CCPM example

In the Paste Plant, periodic shutdowns are planned for major repairs to the vibroformer as well as work on other critical equipment. These repairs must be executed in a way that completes all the planned work (impact on anode quality and equipment reliability) in the designated time (maintain green anode inventory to ensure uninterrupted flow to Anode Baking and Potrooms). A high-level task list for a typical repair is shown in Table I. Task times are traditional estimates, each with safety built in, e.g. the estimate for task A-1 (refurbish former hydraulic power pack) is conservatively estimated at 48 hours just in case any unanticipated work is discovered. The task list and resources are mapped out as a project plan in Figure 14 with an expected completion time of 72 hours.



Task	Est Hrs with safety
F1 - Clean up and shutdown plant	4
A1 - Refurbish hyd power pack	48
B1 - Reassemble former	8
B2 - Test former	8
C1 - Disassemble former	12
D1 - Weld repair cracks in vibroformer table	12
C2 - Replace former airbags – coverweight	8
A2 - Inspect/replace cylinders/hoses on former	8
C3 - Recon vac unit	24
E1 - PLC replace to larger unit	24
E2 - Mod vibro PLC logic	24
A3 - Refurbish hydraulics in green anode handling system	24
A4 - Repair mixer hydraulics	4
D2 - Mixer – rebuild internal wear with weld metal	20
F2 – Start up plant	4

Table I. Task list for a Paste Plant planned shutdown.

Different resources will be required, including specialty skills that will be sourced externally.

A - **External** hydraulics team
B – **In-house** maintainers – team 1
C – **In-house** maintainers – team 2
D - **External** welding team
E – **External** PLC Programming team
F – **In-house** Operations

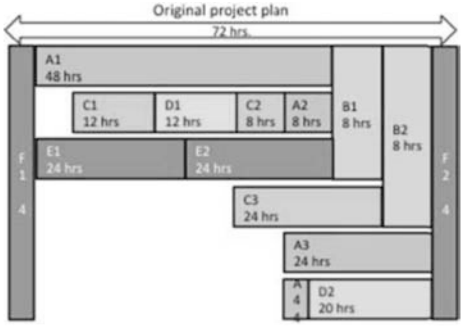
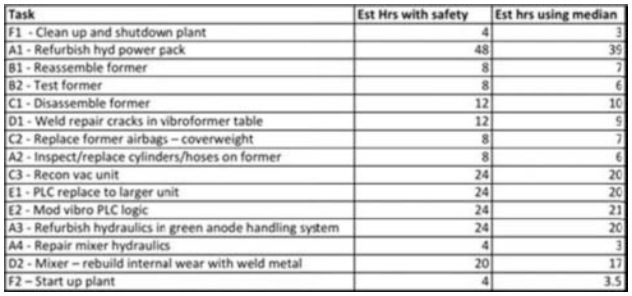


Figure 14. Conventional timeline for the repair. Note that in this planned shut, numerous resource conflicts exist and there is no "clear path" to focus the project manager to ensure execution on time and on budget.

The repair needs a clear focus on a constraint to protect the customer, i.e. to ensure all work is completed in the designated time. Transforming this plan to provide a critical chain and protective buffers is accomplished through CCPM.

The first step is to remove safety from individual tasks and compress time estimates to the "most likely" time from historical data. This results in the task time estimates (at the 50th percentile) in Table II; e.g. task A-1 is re-estimated at 39 hours (the historical median for this task). This results in a revised project plan with new task times and the remainder accumulated in a project buffer as shown in Figure 15.

Removing resource conflicts reveals the critical chain (line through tasks F1–A1–A2–A4–A3–F2, Figure 16) and provides a focus for repair duration. Summing the upper tails of the critical chain tasks gives an estimated repair duration of 74.5 to 88 hours (13.5 hour buffer), with a most likely completion time at 80 hours. This is a very conservative estimate as pooling (as opposed to summing) produces a smaller project buffer. Regardless of how the buffer is set, this is a far more accurate estimate than the original 72 hours and can rationally be used for planning.



Task	Est Hrs with safety	Est hrs using median
F1 - Clean up and shutdown plant	4	3
A1 - Refurbish hyd power pack	48	39
B1 - Reassemble former	8	7
B2 - Test former	8	6
C1 - Disassemble former	12	10
D1 - Weld repair cracks in vibroformer table	12	9
C2 - Replace former airbags – coverweight	8	7
A2 - Inspect/replace cylinders/hoses on former	8	6
C3 - Recon vac unit	24	20
E1 - PLC replace to larger unit	24	20
E2 - Mod vibro PLC logic	24	21
A3 - Refurbish hydraulics in green anode handling system	24	20
A4 - Repair mixer hydraulics	4	3
D2 - Mixer – rebuild internal wear with weld metal	20	17
F2 – Start up plant	4	3.5

Table II. Revised task time estimates.

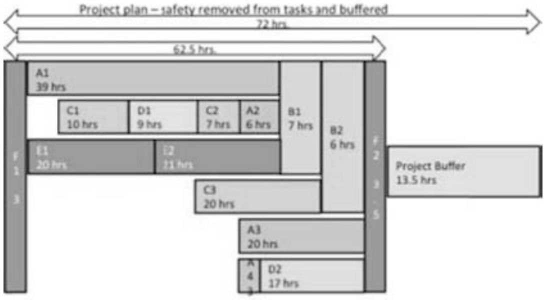


Figure 15. Repair timeline with revised task times and project buffer.

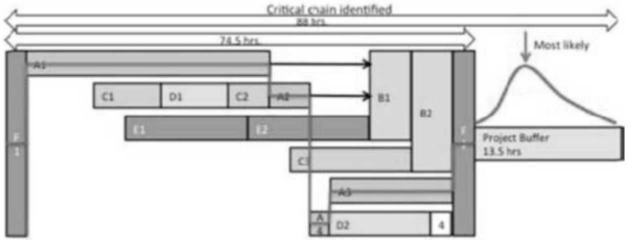


Figure 16. Repair timeline showing the critical chain.

With the critical chain highlighted and resource conflicts removed, "feeder buffers" are added to ensure that work outside of the critical chain occurs to plan and does not take focus from the critical chain. The path E1-E2-B1-B2 is a feeder chain and requires a buffer to ensure all that work is completed before the critical chain ends up at F2. The buffer is determined by pooling the reductions in time estimates for these tasks and creating a buffer (6 hrs.) at the end of the feeder chain (Figure 17). The same is done for the A4-D2 chain. If the creation of feeder buffers results in new resource conflicts (e.g. C2-C3), these are resolved by shifting the work to the left and adding a new feeder buffer (Figure 18).

The original plan (Figure 14) called for a 72-hour repair, but contained numerous resource conflicts, and there wasn't a clear focus on a project constraint. Every task included safety, meaning that "early finish" opportunities are lost and any delays will result in missing the 72-hour target, quite a likely outcome. In addition, unlike the new plan the original plan does not take into account variation in the time to complete tasks.

Fever charts are created to monitor the critical chain as well as the feeder buffers to ensure the project will finish in the expected window of time, with all work complete.

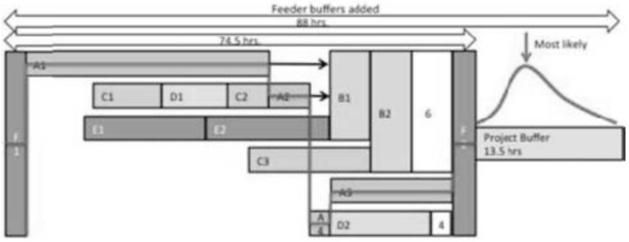


Figure 17. Repair timeline with feeder chain buffers.

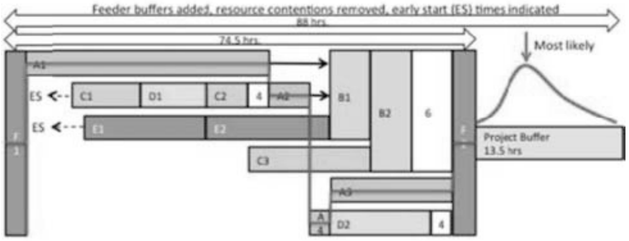


Figure 18. Repair timeline with new resource conflicts resolved.

The CCPM built plan has clear focus – there is a chain of tasks that define the repair duration and they are executed like a relay race – no delays between tasks. The other work chains are designed to start early, run like a relay race and are buffered to ensure they do not negatively impact the repair constraint. Very importantly, with the structure and focus provided by CCPM, repair execution can be analyzed and improved effectively – identifying where to work and what to work on to compress duration, improve quality or reduce cost.

Although we have used a planned shut in the Paste Plant, the tools and methods of CCPM, applied properly within the context of well designed maintenance systems, can deliver results in bake furnace repairs, capital or improvement project planning and execution, and Rodding Room major or routine shuts.

Conclusion

Theory of Constraints delivers the thinking processes, methods and tools to manage systems effectively, avoiding the loss of local optimization. It provides clear focus for throughput improvement and cost reduction efforts that will deliver value for the business as a whole. Within TOC, the same applies through the application of Critical Chain Project Management to projects of all types, providing the thinking skills, tools and methods for project planning and execution, resulting in projects that deliver the results, complete on time and within on-cost.

Both TOC for managing the system, and CCPM for managing a project, provide a rational base for analysis and improvement, leveraging the organizations' ability to focus limited resources on process improvement that delivers business value.

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