AERIAL VIEW OF HEAVY VEHICLE PRODUCTION LINE AT THE MARINE CORPS MAINTENANCE CENTER, ALBANY, GEORGIA.

APPLYING THEORY OF CONSTRAINTS PRINCIPLES AND LEAN THINKING AT THE MARINE CORPS MAINTENANCE CENTER

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The Maintenance Center for the Marine Corps Logistics Base, Albany, Georgia, launched a program in 2001 combining principles drawn from the Theory of Constraints and Lean thinking. The Center had been constantly plagued by apparent capacity shortages in virtually every department and additional manpower was being considered. An analysis using Theory of Constraints revealed that there was, in fact, more than adequate capacity to handle the workload. The perceived lack of capacity was due to policy constraints imposed on the Center as a result of a push scheduling mechanism. By implementing a pull system for scheduling repairs, the Center revealed capacity that had been masked. Today, the Center is ahead of, or on schedule, for 99 percent of the production lines where the Theory of Constraints principles have been implemented.

The Maintenance Center for the Marine Corps Logistics Base, Albany, Georgia, is responsible for the regeneration and reconstitution of the equipment required by the Marine Corps for combat readiness. The Center undertakes complex maintenance operations that include rebuilding equipment to original manufacturer's specifications. It repairs and overhauls a wide variety of products that include small arms, amphibious vehicles, light armored vehicles, fuel tankers, trucks, earthmoving equipment, and logistics vehicle systems.

In 2001, the Center was struggling to complete equipment repairs on time and was coping with an increasing backlog of work. Asking for *plus-ups* or additional time to complete the work had become a normal way of doing business. For instance, on the MK-48 program, entailing overhaul of a heavy-duty hauler for the Marine Corps, the Center was only producing five units a month against a demand of 10 per month. Customers were threatening to divert their orders to the private sector in search for better service.

At that time, scheduling of maintenance operations was based on a Manufacturing Resources Planning II (MRP-II) system that used a push system to load the resources at the Center based on anticipated customer demand. This was resulting in frequent rescheduling and expediting of critical items. The Center's management team reviewed alternate approaches to schedule production and picked one that drew on principles prescribed by the Theory of Constraints (TOC). It contracted with Vector Strategies[1] to implement a *Critical Chain* (Goldratt, 1997) pilot project on the MK-48 vehicle. The Critical Chain is an application of TOC principles specifically tailored for managing complex projects like programs for the overhaul of several major pieces of equipment. The pilot project proved successful and the Center began implementation of the Critical Chain plantwide in April 2002. Used in conjunction with concepts drawn from Lean thinking (Womack & Jones, 1996), this implementation has generated dramatic improvement in the Center's performance.

THE THEORY OF CONSTRAINTS AND THE CRITICAL CHAIN

In the 1980s, Goldratt and Cox (1992) presented Theory of Constraints as a methodology for managing production planning and scheduling. The Theory of Constraints is based on the principle that the goal of any economic enterprise is to make money, now and in the future, and that a system's constraints determine its capacity to make money. Goldratt prescribed a five step *focusing* process to enable a process of ongoing improvement: a) identify the system's constraint(s), b) decide how to exploit the system's constraint(s), c) subordinate everything else to the decision in step b, d) elevate the system's constraint(s), e) return to step 1 if the system's constraints were changed.

In 1997, Goldratt introduced the Critical Chain methodology to apply Theory of Constraints concepts to manage large projects. Program Evaluation and Review Technique (PERT) is probably the single most popular project management tool, and it has been in use for decades. PERT provides the means for identifying the *critical path,* which is the major determinant of the project completion date since the critical path is the single longest chain of linked events embedded in the overall project. The Critical Chain methodology expands on this notion of the critical path and presents a means of determining where buffers should be placed to prevent unplanned disruptions from delaying the project completion.

Figure 1 presents a simple example that illustrates the Critical Chain methodology. This figure represents a project that has four sets of activities that must be completed before a synchronization operation, represented by C4 in the figure, can be completed.

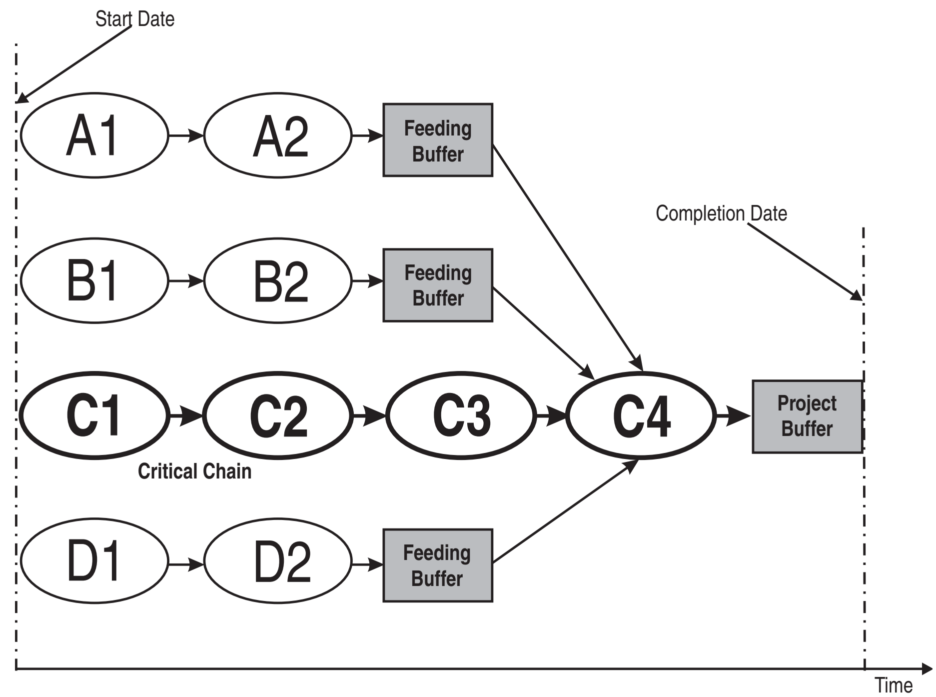

FIGURE 1. THE CRITICAL CHAIN CONCEPT

The synchronization operation could be one of a variety of operations. For instance, in a manufacturing setting it could be an assembly operation, and in a project management setting it could represent the commissioning operation.

PROJECT BUFFERS, FEEDING BUFFERS, AND CAPACITY BUFFERS

The analyst uses historical data to obtain an estimate of the average time for each activity. These are co-mingled to compute the average time it takes each series of activities that must be completed before the assembly operation can begin.

Suppose an analysis reveals that the series of activities with the longest average time is C1-C2-C3. This determines the critical chain[2] that must be monitored the most closely, since any slippage of these items will cause slippage of the overall project. The activities along the critical chain, namely, C1, C2, C3, and C4 are termed critical activities. Activities not on the critical chain are not critical items—they can slip some and not have the overall project slip because their completion takes less time than the completion of the critical chain.

The estimate for the project duration (the lead time) is now obtained as the sum of the average activity times for the critical activities, plus a safety time, termed the *Project Buffer*. This buffers against any variation in the completion times of activities times along the critical chain. The Project Buffer is based on the variance of the total activity time. An overall measure of this variance is obtained simply by summing up the variance (the square of the standard deviation) for each activity.

In addition, for each non-critical activity that feeds a critical activity, a *Feeding Buffer* is placed between the non-critical activity and the critical activity, as illustrated in Figure 1. The Feeding Buffers are determined in a manner similar to the way the Project Buffer is calculated. It must be noted that the Project Buffer and the Feeding Buffers are time buffers and not inventory buffers. That is, variation is *buffered by capacity, rather than inventory*.

With properly sized buffers, the activity along the critical chain that requires inputs from non-critical chain activities has a better chance of being able to start as soon as its predecessor task on the critical chain is complete. This means average throughput time should be reduced. It also means less inventory will be tied up in the system of activities overall.

IMPLEMENTING THE CRITICAL CHAIN AT THE MAINTENANCE CENTER

The overhaul process at the Center starts with disassembly of each vehicle to determine its *work scope*, the amount and nature of the work to be done on that product. The work scope also indicates which parts can be repaired and which parts need to be replaced. Parts that require repair are routed through a series of support shops that include cleaning, blasting, painting, machining, body work, weapons work, and so on. Parts that need replacement are either replaced from existing spare-parts stock or ordered from an external source. Some of these parts are difficult to procure if they are not in stock for a variety of reasons, including obsolescence.

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THE MRP II SCHEDULING SYSTEM

Manufacturing Resources Planning (MRP) is a widely used computer modeling technique that incorporates part lead times and demand forecasts into production plans and schedules. (MRP II is the second generation of such models meant to facilitate just in time production.) At the time the pilot project began, scheduling was based on an MRP II push system. It was a push system in that products were introduced into the shops without regard to the status of the resources dedicated to the repair activities. This led to false starts and delays, increased inventories, and lowered throughput.

Another problem that the MRP II scheduling practice created was that it resulted in multitasking. Multitasking here refers to the fact that some projects (repair jobs) may have activities that require a common resource (employee or machine). When these resources are required to attend to more than one project, the resources are moved between projects even before they complete all the processing on a given project and hand it over to the next activity in the sequence. As a result, each one of the projects involved tends to take more time than if they were completed one-at-a-time from start to finish.

The problem of multitasking at the Center arose as follows. Given the perception that many units had to be disassembled to get parts for units in assembly, it was also believed that disassembled parts should be sent immediately to the support shops, to have as much time as possible to move through the repair cycle. Consequently, many of the resources were subject to multitasking. This is a problem that the Critical Chain is designed to address.

"The root cause of the consistent shortfalls and high inventory levels seemed to be the scheduling system in place that was pushing products out to the shop floor without regard for the status of the resources."

THE BOTTLENECK

As a first step toward applying TOC, the Center's management sought input from throughout the organization on where bottlenecks were believed to be a serious problem limiting output. Opinions varied as to what were and were not bottleneck activities, but every major activity in the Center was believed to be an important bottleneck by at least someone in the facility.

In applying the Theory of Constraints to address the Center's problems, the main shop, where the main products were first disassembled and subsequently reassembled, and the support shops (cleaning, repair, etc.), were modeled as the Critical Chain. The Critical Chain analysis of the data collected revealed that, contrary to everyone's opinion, the facility had more than enough of capacity to carry out the activities required to meet the demand for repair and overhaul of 10 MK-48s per month. The root cause of the consistent shortfalls and high inventory levels seemed to be the scheduling system in place that was pushing products out to the shop floor without regard for the status of the resources. The bottleneck was thus *not a physical resource constraint*. Rather, it was a *policy constraint* introduced by the scheduling process. This discovery allowed Vector Strategies to use a *Simplified Drum-Buffer-Rope*

(S-DBR) technique to model and schedule the activities in the shops that processed components removed from the main products.

THE SIMPLIFIED DRUM-BUFFER-ROPE TECHNIQUE

One of the tools used by TOC to manage production is the Drum-Buffer-Rope (DBR) system. The DBR is a pull-scheduling system that releases material based on a signal from the bottleneck. The traditional DBR model releases orders into the production process such that it synchronizes with the production rate of the least capable resource in the process. This least capable resource is referred to as the capacity-constrained-resource (CCR). If the CCR works at a rate that is less than the rate of output demanded by the customer, then it is the bottleneck. (Otherwise, the external demand rate, *the market*, is the bottleneck.)

In the standard DBR model, the production rate of the CCR is referred to as the *drum*, and the drum beat (production rate of the CCR) paces production for the system. The *rope* in DBR refers to the mechanism that releases work into the production process. The rope is essentially a communication device that ensures that raw material is not introduced into the shop floor at a rate faster than the CCR can handle. If the CCR is not the bottleneck, then the rope ensures that the raw material is not introduced into the shop floor at a rate faster than the customer demand rate. Finally, to prevent the CCR from ever having to wait for work if it becomes free (protect the CCR from being *starved*), a time *buffer* is placed ahead of the CCR to ensure that jobs arrive at the CCR well in advance before they are scheduled for processing at the CCR. Another buffer, called the shipping buffer, protects the situation where the customer's order might be delayed. The standard DBR model is presented in Figure 2.

The standard DBR model requires specialized DBR software to implement it. For enterprises that already have common MRP systems in place, an alternate technique known as the *Simplified* Drum-Buffer-Rope (S-DBR) model can be used, when the enterprise is not constrained by any internal resource (the situation at the Center as revealed by the initial Critical Chain analysis). The drum in S-DBR is based on firm orders. As orders come in, a quick check is made on the total load on the CCR. If the CCR is not too heavily loaded, the order is accepted and released into the shop floor for processing. The only buffer maintained is the shipping buffer. The rope is no longer tied to the CCR schedule. Instead, the material release schedule is directly generated by firm orders received. See Figure 3.

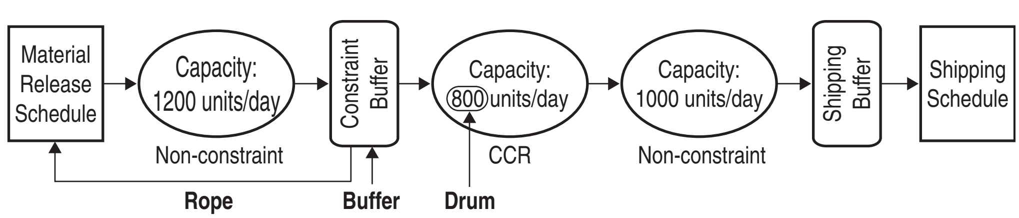

FIGURE 2. THE TRADITIONAL DRUM-BUFFER-ROPE MODEL

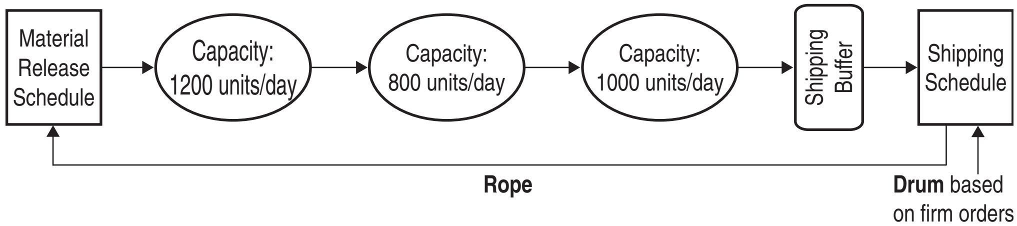

FIGURE 3. THE SIMPLIFIED DRUM-BUFFER-ROPE MODEL

The S-DBR model has some advantages. It does not require any specialized software, and this can be a significant benefit for enterprises that might be unwilling or unable to invest in specialized DBR software (Schragenheim & Dettmer, 2000). Another advantage of the S-DBR approach is that it does not have to require two buffers, but needs just one. Finally, the S-DBR approach is more focused on market demand and ties the organization to its customers more directly.

RESULTS FROM THE IMPLEMENTATION OF CRITICAL CHAIN AND S-DBR

The Center was able to use an S-DBR approach to scheduling in conjunction with the existing MRP II business system as described above. Only the Critical Chain portion of their solution required additional software.[3] The MRP II system that was used for scheduling now facilitates the S-DBR schedules. The MRP II database also stores data on lead times for items supplied by vendors.

Table 1 presents the results of implementing the Critical Chain on the MK-48 and the LAV-25, the landing assault vehicle that was the focus of the second Theory of Constraints/Critical Chain implementation effort.

As Table 1 indicates, repair cycle times for the MK-48 were reduced by a factor of 3, from an average of 167 days to an average of 58 days. For the LAV-25, the corresponding figures were 212 days and 119 days, before and after. The

TABLE 1. RESULTS ON THE MK-48 AND LAV-25 LINES

	Repair Cycle Time (Days)			Units in WIP/Monthly Demand		
Line	Before	TOC/CC*	After	Before	TOC/CC*	After
MK48	167	52	58	5.5	1.75	1.4
LAV-25	212	99	119	4.3	3.2	3.1

*Formulated cycle times and work in progress based on analysis of Theory of Constraints and Critical Chain.

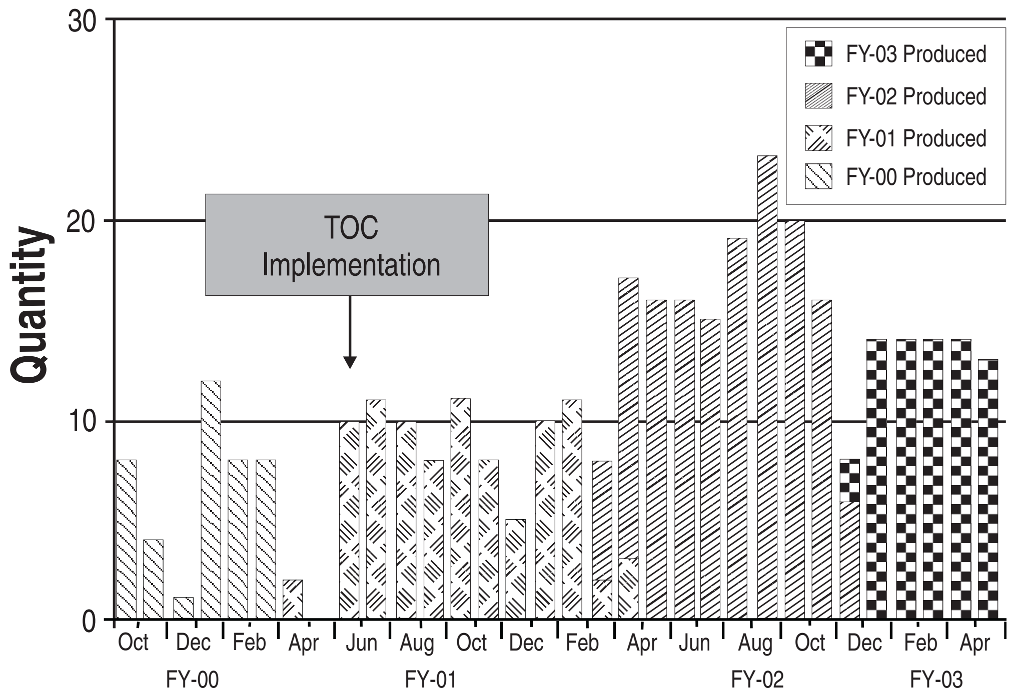

FIGURE 4. MK-48 MONTHLY OUTPUT

work in process levels (relative to demand) was also reduced significantly, as shown in the table. Other products showed similar reductions in cycle times and work in process.

The cost to repair products also went down by 25 to 30 percent, mainly because the reduction in delays resulted in more throughput without any increase in the cost of repair. All the product lines are now 99 percent on schedule to customer requirements. Figure 4 shows the increase in output realized on the MK-48 line. The capacity for the MK-48 line is now much more flexible, and can work with a rate of anywhere between 10 units per month to as high as 23 units per month, as indicated by the figure.

COMBINING LEAN THINKING WITH TOC PRINCIPLES

The principles in Theory of Constraints can be used in conjunction with Lean thinking to leverage even more benefits for the enterprise. Like Theory of Constraints, Lean thinking is a means of enabling a growth strategy.[4] Unlike Theory of Constraints, which primarily focuses on the bottleneck, Lean thinking is focused on reducing waste at all levels and in the process of doing so, it uncovers additional capacity that could be deployed for further growth.

At the Maintenance Center, a corporate plan was developed for implementation of Lean thinking and a Lean team was set up. Some of the results of the

Lean efforts resulted in the Center being subject to a 6-S activity and a reengineering of the supply warehouse. (6-S is a set of practices aimed at cleaning and organizing a workplace to improve operations and safety.) The 6-S activity resulted in a significant increase in available shop floor space. Hundreds of man-hours associated with the testing and repair of cables on the Assault Amphibious Vehicle (AAV) and Light Armored Vehicle (LAV) family of vehicles were saved. Tools in excess of $200,000 were turned in for redistribution and future use. The process flows in production work centers were streamlined. Another major benefit from the convergence of Lean thinking and TOC was that it resulted in increased morale for the employees of the Center. The workplace is cleaner, less cluttered, and safer. The Center has become extremely flexible and better positioned to meet its responsibilities for regeneration and reconstitution of critical supplies.

CONCLUSION

Managing a maintenance, repair, and overhaul (MRO) facility is a more challenging task than managing most manufacturing facilities because of the high degree of uncertainty that prevails in repair operations. Unlike a typical flow shop manufacturing setting where the enterprise knows the sequence of operations required to complete the finished product, the MRO facility is very much like a pure job shop facility. In the MRO facility, the work scope of a product that arrives at the facility is not known unless the product is disassembled and inspected. There is a tremendous variation in the work scope even for the same type of product, such as the MK-48, and it is difficult to accurately predict the percentage of parts that must be replaced and the percentage of parts that should be repaired. To add to the complexity, the original manufacturer may no longer produce the parts that have to be replaced.

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As Vector Strategies observed, the magnitude of culture change was greatest in the support shops through which disassembled parts are routed for repair. Holding disassembled parts for release caused great fear among the workforce, and resistance was substantial. This aspect of the implementation was the last part of the culture change accepted and accomplished by the Maintenance Center. But as they saw significant improvement with every other aspect of the implementation, they gained the courage to move forward.

The work carried out to date has made the Albany Maintenance Center a showcase of world-class overhaul and repair performance. Weekly tours are conducted, hosting officers and executives from government and private overhaul and repair operations. The Center's Web site (www.ala.usmc.mil/maintctr) and monthly reports prominently features Theory of Constraints and Lean applications. Although the Center has achieved significant successes, Theory of Constraints and Lean thinking are a process of on-going improvement. One instance of improvement that may be a candidate for future consideration is the manner in which products are repaired. Currently, the mode of operation is to employ a station-build. The Center could consider operating the repair facility as a flow-cell using a moving line. This is a subject of future research.

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ENDNOTES

1. http://www.vectorstrategies.com

2. We will use the lower case (critical chain) to identify the set of activities that must be most closely monitored and the upper case (Critical Chain) to identify the methodology.

3. This software, *Concerto*, was procured from Realization Technologies.

4. Sprovieri interview with Tom Greenwood.

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