PRACTICAL APPLICATION OF DRUM-BUFFER-ROPE TO SYNCHRONIZE A TWO-STAGE SUPPLY CHAIN

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This case study outlines the operational aspects of a synchronized supply chain that exemplifies the APICS supply chain management principles “synchronize supply with demand” and “measure performance globally” [13]. In this case the supply chain delivered electronic instrumentation produced at a single factory location in the United States to customers in South Korea, Singapore, Texas, Germany, and Scandinavia. The product line consisted of a product family with nine low-volume models and five highly volatile, medium-volume models. The composite bill of materials (BOM) for the product line included approximately 450 part numbers procured from approximately 105 suppliers. One of the suppliers, the printed circuit assembly (PCA) supplier, was a U.S.-based contract manufacturer. Most of the supplier base was managed by the PCA supplier’s procurement group.

The products were sold into the highly competitive market of cell phone component manufacturing, in which missed ship dates meant the loss of market share. Factory management was frustrated by its inconsistent supplier response time (SRT) performance, which had been running from three to five weeks depending on the model. The market demanded a two-week SRT. The factory was tied to a legacy material requirements planning (MRP) system that allowed several weeks between the receipt of a customer order and the release of purchase orders to lower-level suppliers. The production line had been organized as a build-to-stock operation. The factory had tried to compensate for a volatile forecast by overplanning and by making a significant investment in purchased parts inventory, yet it suffered from random backorders and production bottlenecks. Some managers felt that the upcoming corporate implementation of an ERP system would save the day, but this particular factory was not scheduled for ERP implementation anytime soon. While looking for other alternatives, factory managers began to explore the trade-offs of switching to a build-to-order operation. They soon became attracted to the idea of synchronizing the supply chain as a means of improving and sustaining SRT. However, there were many questions and practical issues to be resolved before such a synchronized solution could be embraced:

- How much could the SRT be improved?
- How much of the supply chain could be synchronized?
- What investment in capacity and inventory would be needed to synchronize?
- To what degree would changes in production rate and mix be accommodated?
- How would the cooperation among trading partners have to change?
- How would planning and procurement have to operate?
- What performance measures would be needed to keep operations aligned?

The answers to these questions and the solutions to these issues were found in the concepts of drum-buffer-rope from Eli Goldratt’s theory of constraints (TOC) applied across the entire supply chain.

DRUM-BUFFER-ROPE AND APICS ADVANCED SUPPLY CHAIN MANAGEMENT

The drum-buffer-rope concepts were first introduced by Eli Goldratt in The Goal and applied to the context of a manufacturing plant [3]. This foundation of TOC has been refined in the area of financial measures and buffer management by Debra Smith and others [5, 9] and in the simplification of drum-buffer-rope by Schragenheim and Dettmer [6]. Covington documented an early application of TOC to a textile/apparel supply chain [2], and Walker described the application of drum-buffer-rope to supply chain management [1, 10, 12]. Two APICS advanced supply chain management principles, “synchronize supply with demand” and “measure performance globally,” are grounded largely in Goldratt’s TOC [1, 13].

In the TOC production model the drum is the constraint that limits the factory’s throughput and its ability to make money. The buffer is the safety time that prevents the statistical variation in a serial process from degrading its throughput. Goldratt describes the need...
for both a shipping buffer and a protective buffer. The shipping buffer creates a safety time against statistical variation between the system constraint and the end of the production line. The protective buffer creates a safety time against statistical variation between the start of the production line and the system constraint. The rope is the synchronization signal that ties customer demand to the constraint and the constraint to the starting work center. The rope synchronizes the release of new work to the capability of the drum and to the actual demand of the customer. The throughput of the factory is optimized when the drum, buffer, and rope work together.

Consider a supply chain defined by a sequential arrangement of the trading partners, each with statistical variation in its operations. One of the supply chain trading partners owns the limiting capacity. This trading partner is the system constraint (drum), and will limit the end-to-end throughput of the entire supply chain [12]. To optimize throughput and system inventory the supply chain must identify and manage a shipping buffer and a protective buffer (buffer) as safety time against statistical variation [12]. The supply chain, in addition, must connect the market demand signal to the system constraint and the starting work centers for each of the trading partners (rope) to send the synchronization signal [12]. Drum-buffer-rope is applied to “synchronize supply with demand.” Finally, equivalent throughput and total system inventory are used to “measure performance globally” to keep the supply chain trading partners in continuous operational alignment [12].

**UNDERSTAND MARKET DEMAND AND CUSTOMER REQUIREMENTS**

The starting point was a clear understanding of the market demand and the customer’s delivery expectation. Table 1 details a six-month order history period. Customers said they expected immediate shipment of 10 units or less, but were willing to wait up to two weeks for orders of 100 to 200 units. Particular orders were lumpy with a small order for evaluation units, followed by a two-month lull, followed by one or two very large quantity orders. In addition, the sales force was on commission, and was motivated to maximize sales at the end of each quarter. This superimposed an end of the quarter sales seasonality on top of an already lumpy demand pattern. Each customer expected reliable, consistent, on-time delivery.

**DETERMINE WHERE SYNCHRONIZATION APPLIES**

The application of synchronization is limited in two ways. First, synchronization requires that in moving upstream from the customer toward the supplier the value-adding cycle times of each successive trading partner be kept within the customer’s desired order-to-delivery cycle time. A pull system, like synchronization, breaks down at the point in the supply chain at which cumulative cycle time begins to exceed the desired customer order-to-delivery cycle time [11]. Beyond that point upstream trading partners cannot keep up with the rate of production without inventory buffers. It was determined that the factory could receive and process the order, complete production, transport the product by air freight, and clear customs into South Korea, Singapore, and the European Union in 10 working days. That meant an SRT of 2 weeks was achievable.

Second, the shape of the profile of the BOM working from the top to the bottom determines the applicability of synchronization [11]. The BOM for these products resembled a “head and shoulders” profile. At level 0 and level 1 of the BOM only a few parts and assemblies from a small number of suppliers were required. But by level 2, which defined the loaded printed circuit boards, the width of the BOM exploded into hundreds of parts and dozens of suppliers. Synchronization breaks down

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**TABLE 1: Demand History**

<table>
<thead>
<tr>
<th>Product</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Actual SRT/Target SRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td>6</td>
<td>3</td>
<td>3 weeks/2 weeks</td>
</tr>
<tr>
<td>Model B</td>
<td>12</td>
<td>4</td>
<td>3 weeks/2 weeks</td>
</tr>
<tr>
<td>Model C</td>
<td>26</td>
<td>8</td>
<td>4 weeks/2 weeks</td>
</tr>
<tr>
<td>Model D</td>
<td>18</td>
<td>9</td>
<td>3 weeks/2 weeks</td>
</tr>
<tr>
<td>Model E</td>
<td>8</td>
<td>11</td>
<td>5 weeks/2 weeks</td>
</tr>
<tr>
<td>Model F</td>
<td>5</td>
<td>18</td>
<td>5 weeks/2 weeks</td>
</tr>
<tr>
<td>Model G</td>
<td>44</td>
<td>18</td>
<td>3 weeks/2 weeks</td>
</tr>
<tr>
<td>Model H</td>
<td>44</td>
<td>19</td>
<td>4 weeks/2 weeks</td>
</tr>
<tr>
<td>Model I</td>
<td>61</td>
<td>45</td>
<td>4 weeks/2 weeks</td>
</tr>
<tr>
<td>Model J</td>
<td>182</td>
<td>112</td>
<td>4 weeks/2 weeks</td>
</tr>
<tr>
<td>Model K</td>
<td>149</td>
<td>129</td>
<td>5 weeks/2 weeks</td>
</tr>
<tr>
<td>Model L</td>
<td>166</td>
<td>133</td>
<td>5 weeks/2 weeks</td>
</tr>
<tr>
<td>Model M</td>
<td>399</td>
<td>204</td>
<td>3 weeks/2 weeks</td>
</tr>
<tr>
<td>Model N</td>
<td>404</td>
<td>219</td>
<td>4 weeks/2 weeks</td>
</tr>
</tbody>
</table>

Total = 1524 RMS\(^b\) = 374

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*a* In units per month based on 6 months of actual sales.

*b* RMS = root mean square.
at the transition point from the head, with few suppliers and few parts, to the shoulders, with many suppliers and many parts. The traditional push system of MRP must take over through the bottom of the BOM. In this product line the transition in the BOM from the head to the shoulders defines the push/pull boundary for supply chain operations.

DEFINE THE SUPPLY CHAIN COMMUNITY

The architecture of a supply chain is defined through the relationships of its trading partners. “A trading partner is an organization outside the firm that plays an integral role within the supply chain community, and whose financial fortune depends on the success of the supply chain community” [13]. In this supply chain the factory, the sheet metal supplier, the PCA supplier, and a custom semiconductor supplier were trading partners. The logistics service providers and most of the lower-level electronic parts suppliers, although essential to the product, were nominal trading partners. This meant their financial success was largely independent of this particular supply chain. A nominal trading partner cannot be expected to participate in synchronized operations. Figure 1 diagrams this supply chain and differentiates trading partner nodes from nominal trading partner nodes.

Un fortunately, the product design was old, and the individual product models took on their identity early in the upstream flow of the supply chain. If that were not the case, and the upstream flow was generic across the product family, it would have been a good opportunity to organize a downstream postponement operation. One of the first components to be manufactured in the factory was the power transformer. The 14 product models required 11 different power transformers. Individual power transformers were then mounted onto one of three sheet metal chassis, and primary wiring was added. One of 4 front-panel subassemblies and 1 of 14 printed circuit assemblies were joined to the chassis in the factory at the initial assembly work center. At this point the product was turned on, and put into an aging rack to drive out any early component failures. Once the age process was successfully completed, the covers and a handle were added in final assembly. The product then completed an electrical safety test and final electrical performance tests in the factory before being packaged on the production line for shipment. When a product failed any of the testing, it was returned to a repair work center, then recycled through age and retested.

In summary, a few raw materials became 11 transformers, 1 type of raw material plus hardware became 3 chassis,
hundreds of purchased parts became 14 PCAs and, with a few additional purchased parts, became 14 products.

**DECIDE WHICH OF THE TRADING PARTNERS TO SYNCHRONIZE**

Determining where to synchronize can be difficult. The reorder cycle time plus the manufacturing cycle time plus the outbound logistics transit time between inventory points in the supply chain must be compared against the customer order-to-delivery cycle time goal [12]. This is similar to, but different from, line balancing in a factory. The question to ask is, can the reorder be placed and the replenishment done reliably in the allotted time? In this supply chain the aging process was a natural inventory point. The head to shoulders transition at the beginning of the PCA supplier’s process was a second natural inventory point. Table 2 analyzes the reorder-to-replenishment cycle time elements versus the customer order-to-delivery goal.

The cycle time analysis shows that the trading partners to be included in the synchronization are the factory (final assembly and test, initial assembly, and transformer fabrication), sheet metal fabricator, and PCA supplier. Notice that the inventory point at aging splits the factory into two different order-to-delivery loops. In addition, the factory aging process and initial assembly times are included as part of the total reorder-to-replenishment cycle times for transformer fabrication, sheet metal fabrication, and PCA assembly. The reason is that one transformer, one sheet metal chassis, and one printed circuit assembly flow together to become one product without any additional inventory buffering. Figure 2 shows how the synchronized portion of this supply chain can be represented by a two-stage supply chain model. The aging process can be viewed as a time delay in the flow, much like transit time. The custom semiconductor trading partner is excluded from synchronization because its cycle time exceeds the required 10 days. The raw material distributor of galvanized sheet metal is also excluded from the synchronization because it is a nominal trading partner.

**SET THE CAPACITY FOR A CAPABLE SUPPLY CHAIN (THE DRUM)**

In a synchronized supply chain every node, or trading partner, that is included in the synchronized operation must be capable. *Capable* means that the trading partner is willing to invest in sufficient capacity to meet the maximum daily throughput requirement [12]. The three factors used to determine capable capacity are the required customer service level, the minimum to maximum range of daily production, and the potential to grow beyond the maximum range. The 14 products in this supply chain example varied from a mean of 5 units

<table>
<thead>
<tr>
<th>Supply Chain Path</th>
<th>Cycle Time</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Order + final assembly and test + transportation</td>
<td>10 days</td>
<td>Okay to synchronize. This sets the goal.</td>
</tr>
<tr>
<td><strong>Factory Aging Process</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Xformer + initial assembly reorder-to-replenishment</td>
<td>Less than 10 days</td>
<td>Okay to synchronize. Includes the aging cycle time.</td>
</tr>
<tr>
<td>3. Sheet metal reorder-to-replenishment</td>
<td>Less than 10 days</td>
<td>Okay to synchronize. Includes part of cycle time #2.</td>
</tr>
<tr>
<td>4. Galvanized sheet reorder-to-replenishment</td>
<td>Less than 10 days</td>
<td>Not synchronized. Nominal trading partner. Use MRP.</td>
</tr>
<tr>
<td>5. PCA assembly reorder-to-replenishment</td>
<td>Less than 10 days</td>
<td>Okay to synchronize. Includes part of cycle time #2.</td>
</tr>
<tr>
<td>6. Custom semiconductor reorder-to-replenishment</td>
<td>Less than 10 days</td>
<td>Not synchronized. Manage with MRP.</td>
</tr>
<tr>
<td><strong>PCA Push/Pull Boundary</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Purchased part reorder-to-replenishment</td>
<td>More than 10 days</td>
<td>Not synchronized. Cycle time too long. Use MRP.</td>
</tr>
</tbody>
</table>

**TABLE 2: Supply Chain Cycle Time Analysis**

Customer order-to-delivery goal = SRT of 10 days

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per month with a standard deviation of 11 units per month to a mean of 404 units per month with a standard deviation of 219 units per month. When the historical market demand for all 14 products was combined statistically, the total mean was 1,524 units per month with a root mean squared (RMS) combined standard deviation of 374 units per month. It is valid to approximate the combined standard deviation using an RMS calculation because the market demand for each product was independent of the market demand for the other products; there was little autocorrelation between product demands. Using an average of 21.5 work days per month, this supply chain needed to be capable of mixed-model production with a combined mean of 71 units per day and a combined RMS standard deviation of 17.4 units per day.

To achieve a 95% confidence level so that the target 10-day SRT could be maintained, each of the trading partners had to agree to a capable capacity investment equal to the mean plus two standard deviations of the historical market demand, or 106 units per day. This meant that 19 out of 20 days the supply chain would be able to deliver to a 10-day SRT no matter what the market demanded. There were four contenders for the system constraint: the capacity of the final test set, capacity of the aging process, capacity of a welding machine in magnetics fabrication, and capacity of the surface mount line at PCA assembly. It was determined by careful measurement that the welding machine in transformer fabrication was the most constraining of the four; welding was the system constraint.

The minimum operating capacity is a second factor to consider in a synchronized operation. The rate of the market demand fluctuated day to day. One day a month, or 5% of the time, the demand for product would go as low as the mean minus two standard deviations or 36 units per day. That is only one-third of the maximum capacity for this line. It meant that culturally the workforce had to be willing and able to cross train, work on quality projects, or work for a day on another production line. Therefore, culturally, management had to understand that to achieve a 95% or higher service level some capacity would be idle part of the time. The return on investment of such capacity is driven by end-to-end supply chain throughput, not by machine utilization. It may be prudent for part of the workforce to be hired as temporary workers to add flexibility in managing capacity.

The probability of growth in market share is the third capacity consideration. The system constraint must be sized to achieve the customer service level while maintaining surge capacity at each of the other supply chain nodes. If the product line is expected to grow, by say 20% during the next year, then either today’s loading on the system constraint must be reduced by 20%, or 20% incremental capacity must be purchased and added to the system constraint in the necessary time frame. As the system constraint capacity is adjusted, a check must be made to ensure that the real system constraint has not shifted to another trading partner.
LEARN SYNCHRONIZED INVENTORY DYNAMICS (THE BUFFER)

Think of a synchronized supply chain as a sequence of trading partners arranged serially. The output of each upstream trading partner is connected by an outbound pipeline to the input of the next downstream trading partner. The last outbound pipeline connects directly with the end customer. Each stage of the supply chain network consists then of a trading partner node with its outbound pipeline. In a synchronized supply chain, each node must be preloaded with inventory before operations can begin. This preload inventory makes each node capable of supporting the maximum throughput set by the system constraint. When the market demand is high, inventory transfers out of the node and into the pipeline. When market demand is low, inventory transfers out of the pipeline back into the node.

In the interest of not creating any more inventory than absolutely necessary, the quantity of inventory held in the aging process also functioned as the shipping buffer. This provided about two days of time buffer to solve any upstream issues, while still shipping on time. This was practical only when the final test set would fail at random times, and the line would run out of packaging materials. Packaging was ordered weekly by the MRP system. A second test set was built with duplicate capability and new protection circuitry that dramatically increased its uptime. And the test supervisor began ordering packaging direct from the supplier on the basis of the actual daily demand.

Likewise, the level of raw materials held in transformer fabrication also functioned as the protective buffer for the welding machine, which was the system constraint. This was practical only after the winding, terminating, and stacking process between the raw material inventory and the welding machine had been shown to be predictable and reliable. Because this was not the case with a constantly changing transformer mix, two days of work-in-process inventory was completed through the stacking operation and physically stored beside the welding machine. Of course, there was also purchased material inventory at the PCA supplier push/pull boundary, and there was raw material at the sheet metal fabricator.

The preload buffer inventory quantities are calculated from the equations presented in figure 3. A two-stage synchronized supply chain reference model is shown in the lower right portion of the figure. Each node has an associated cycle time and outbound pipeline transit time. The preload buffer inventory quantities for each node are calculated on the basis of the maximum throughput of the system constraint and the ratios of cycle times and pipeline transit times. The quadrant with the appropriate pair of equations is determined...
on the basis of whether the cycle time for node$_2$ is larger or smaller than for node$_1$, and whether the transit time for node$_2$ is larger or smaller than for node$_1$. The equations found in the upper-right quadrant were used for this example. The preload inventory for final assembly was 212 units at aging. The preload inventory for node$_2$ included 106 transformers in magnetics fabrication, 106 chassis in sheet metal fabrication, and 106 printed circuit assemblies at the PCA supplier. Once synchronized operations began, these quantities naturally split between inventory at the node and inventory in the pipeline.

**BROADCAST THE CUSTOMER’S DEMAND (THE ROPE)**

It is common knowledge that a long serial supply chain will exhibit the “bullwhip effect” [4, 7, 8]. That means the replenishment signal for a small change in customer demand becomes distorted and amplified as it propagates upstream toward the supplier. As a result, the supplier is bullwhipped from periods of overproduction to periods of no production. The bullwhip effect is caused by the combination of an upstream serial transmission of demand information between pairs of trading partners and a downstream delay in logistics transit time between pairs of trading partners. The bullwhip effect must be eliminated for a synchronized supply chain to be effective.

The proper way to minimize the bullwhip effect is to connect every trading partner in parallel to two demand signals. One demand signal, the actual demand, originates from the point of sale at the customer. The second demand signal, the broadcast demand, originates from the system constraint. The actual demand signal is used to synchronize the shipping buffer with the system constraint and with the rate of inbound materials flowing into the push/pull boundary. The broadcast demand is used to synchronize all the other pull trading partners [12]. In this supply chain the actual demand was routed in parallel to the aging process (shipping buffer), to the welding operation in transformer fabrication (system constraint), and to the PCA supplier’s materials planning system (push/pull boundary). The welding operation (system constraint) then forwarded the broadcast demand in parallel to the first operation in final assembly, initial assembly, magnetics fabrication, sheet metal fabrication, and PCA assembly.

A set of daily operating rules determines the action to be taken by each of the trading partners downstream from the push/pull boundary. Should the system constraint move to another trading partner, every trading partner already has simultaneous access to both demand signals. Should the system constraint shift, an orderly changeover of system constraint roles and responsibilities can take place.

Supply chain synchronization requires adherence to the following operational rules:

- **Rule 1**: The customer end of the supply chain ships the actual demand rate and mix from its shipping buffer.
- **Rule 2A**: If the system constraint can meet the actual demand rate and mix, then it broadcasts the actual demand rate and mix as the broadcast demand.
- **Rule 2B**: If the system constraint cannot meet the actual demand rate or mix, then it broadcasts a constrained rate or mix as the broadcast demand, and it alone manages the customer order backlog, until throughput is caught up.
- **Rule 3**: Each day all other pull trading partners produce the equivalent number of products or assemblies required by the rate and mix of the broadcast demand.
- **Rule 4**: The push/pull boundary replenishes raw materials and purchased parts at the accumulated rate and mix of the actual demand” [11].

**PLAN AT THE PUSH/PULL BOUNDARY**

A pull system expects all the required material to be immediately available as needed. The buffer inventory that defines the push/pull boundary at the PCA supplier is replenished using the traditional production and inventory control methods of forecasting, sales and operations planning, master production scheduling (MPS), and MRP. It is essential that the rate and mix of market demand be forecast in units at least monthly. Forecast error is tracked against the rate and mix of the actual demand. In this supply chain raw materials and lower-level components for transformer fabrication, sheet metal fabrication, and PCA assembly were each replenished using MRP.

The push/pull boundary inventory at the PCA supplier contained component parts that were both common across the 14 end products and unique to only one product. The part levels maintained in this inventory buffer were key to the supply chain’s ability to meet dynamic changes in product mix. When a part is common, it requires less safety stock because of the risk-pooling effect [8]. Risk pooling takes into account the statistical probability that with independently demanded products an increase in demand of one product is likely to be counterbalanced by a decrease in demand of another product that uses the same part.
This looks like a smaller standard deviation in the part’s demand relative to the demand for a unique part. But when a part is unique, the standard deviation in that part’s demand appears to be larger relative to that of a common part. To guarantee a 95% service level, the part safety stock must be planned to cover the mean plus two standard deviations of the historical product demand times quantity usage per end product.

The MPS was managed to maximize the upside potential in a competitive, growing market. The plan for the first six weeks of the MPS was to build the maximum throughput per day, or 530 units/week. The remaining plan through the end of the MPS planning horizon was to build at a rate and mix equal to the mean of the historical data, or 355 units/week. Following rule 4, discussed above, actual daily orders were accumulated Monday through Friday of the current week. Every Friday the MPS plan for the following week was adjusted down to match the previous week’s actual demand. And every Friday the sixth week’s plan was raised to the maximum throughput of 530 units/week. By overdriving the front end of the MPS in this fashion, the planner could push out unnecessary production starts of PCAs, and the buyer could push out or cancel unnecessary purchases. Yet, the rate of incoming material would sustain the maximum throughput with 6 weeks of lead time for suppliers to react. The cost for this inventory shock absorber was 6 weeks $\times$ [530 units/week – 355 units/week] equaling 1,050 sets of lower-level parts. This was about 15 days supply of lower-level inventory on the basis of historical demand held by the PCA supplier.

**KEEP THE SUPPLY CHAIN IN ALIGNMENT WITH EQUIVALENT THROUGHPUT AND TOTAL SYSTEM INVENTORY PERFORMANCE MEASURES**

A pair of global performance measures, equivalent throughput and total system inventory, are used to keep the daily operations at each of the trading partners in alignment with the product line business strategy. These are global measures in that they serve to globally optimize the end-to-end supply chain, rather that just locally optimizing the operations of one trading partner [10]. Go back for a moment to the idea of an idealized synchronized supply chain that has just one stockkeeping unit (SKU) moving through a series of downstream trading partners before reaching the end customer. Suppose that this SKU is not modified in any way as it is pulled downstream through the supply chain. If all the trading partners are in alignment, the throughput of product entering each section of outbound pipeline will be the same. And the sum of each trading partner’s node inventory and its outbound pipeline inventory will be constant and equal to the preload inventory for each of the middle nodes. In fact, the total system inventory will be the number of nodes times the preload inventory. But if one of the trading partners begins to fall out of alignment, its throughput and residual node inventory will deviate from the other trading partners.

In the real world this idealized model must be adjusted to account for three factors. First, not one SKU, but many SKUs, are being produced. Second, the product exists only as equivalent sets of lower-level parts, as one moves upstream toward the supplier. And third, different trading partners have different manufacturing cycle times and different outbound pipeline transit times. Some adjustments must be made to account for these differences.

“A synchronized supply chain is in alignment when the units per day of throughput for one trading partner, offset in time by that trading partner’s fixed cycle time, is equivalent to the units per day of throughput for each of the synchronized trading partners. This is the equivalent throughput performance measure.

- Throughput is measured in units entering the outbound pipeline.
- Throughput at the trading partner node is offset by the amount of fixed cycle time in days that this node requires to convert an order into a shipment.
- Throughput is independent of transit time.
- The bill of material defines the equivalency of part sets to the end product.
- Alignment is lost upstream from the push/pull boundary.” (Written by the author for the APICS Advanced Supply Chain Management (ASCM) courseware, © 2000 APICS.)
Inventory is measured in units remaining at the node and entering the pipeline.

The most downstream node (closest to the customer) is the reference node.

The preload inventory level for each synchronized trading partner is adjusted by the ratios of transit times and cycle times to the reference node.

The bill of material defines the equivalency of part sets to the end product.

Alignment is lost upstream from the push/pull boundary. (Written by the author for the APICS ASCM courseware, © 2000 APICS.)

A supply chain is synchronized when...

For the last supply chain stage,
- daily ending inventory, \([\text{node + pipeline}] = \text{daily starting inventory, [node + pipeline]} + \text{current broadcast demand} - \text{last broadcast demand.}\)

For the next to last supply chain stage,
- daily equivalent end inventory, \[\text{preload equivalent inventory,} - \text{current broadcast demand.}\]

Figure 4 shows simulation results for this example and illustrates the dynamics of the daily equivalent throughput and total system inventory performance measures when the supply chain is synchronized. Figure 4a details the model’s setup and resulting performance measures. Figure 4b shows simulated data for four periods at each node and in each pipeline.

MANAGE THE DYNAMICS OF DEMAND RAMPING UP AND RAMPING DOWN

Over time the operating levels of any supply chain will change. Market conditions might improve or they might worsen. A particular product might suddenly become more popular and radically change the product mix. The key to managing such up and down dynamics is the ability to know when the supply chain operating point falls outside the dynamic range for which it has been designed. Once a month the mean and RMS standard deviation are recomputed for the entire product family on the basis of the past six months of actual demand. The new month 6 demand data are added, and the old month 1 demand data are subtracted to arrive at a new six-month history. Product mix safety stock levels for each of the inventory buffers are recomputed monthly using these revised historical demand data.

The supply chain capacity was designed to sustain...
a 95% service level over the range of the mean demand 
+2 standard deviations of the demand. The supply chain buffer inventory has been sized to sustain this maximum throughput rate over the six-month historical product mix. In a steadily rising market, incremental inventory must be added to each node and incremental capacity added to the system constraint before actual daily throughput can consistently exceed the maximum throughput. Otherwise, the synchronization will be broken. Likewise, in a steadily falling market some inventory must be subtracted from each node and some capacity taken away from the system constraint to maintain a reasonable return on inventory and capacity investments.

Once a month the past 20-day actual mean throughput is computed across all 14 product models. This is checked against upper and lower control limits with an eye on the sales forecast. As the 20-day actual mean throughput approaches either control limit, the operating design of the synchronized supply chain must change. The control limits should take into account both underlying trends in the actual demand and the calendar time it will take to implement the required changes to capacity and inventory. On the one hand these triggers should not cause volatility in planning capacity and inventory, but on the other hand they should catch significant upward and downward trends in time to adjust capacity and inventory.

Upper control limit = trigger to buy some node capacity and inventory
Upper control limit = mean capacity + 25% = 89 average units/day

Lower control limit = trigger to sell some node capacity and inventory
Lower control limit = mean capacity – 25% = 53 average units/day

**SUMMARY**

This case study presented a detailed description of the synchronization of the final two stages of an international supply chain for an electronics instrumentation manufacturer. The product line was transformed from a traditional MRP-driven build-to-stock manufacturing operation into a build-to-order synchronized supply chain. That transformation successfully reduced the supplier response time from an inconsistent 3–5 weeks to a consistent 10 days across all products. The practical application of Eli Goldratt’s drum-buffer-rope TOC concepts to synchronize the supply chain resulted in excellent delivery performance for a medium investment in capacity, inventory, and information management. The supply chain redesign objective was accomplished, and synchronization was sustained during many months of volatile demand.
The following is a summary of the practical lessons learned from this case:

- **Drum**: Define capacity in daily equivalent units. Use historical statistical demand information to determine the capacity required by each node to maintain a 95% service level. The capacity investment was described in terms of every trading partner being capable of the maximum daily throughput. This means some excess capacity at most trading partner sites and the need to maintain a flexible workforce. The process downstream from the system constraint must be totally reliable. Be prepared to adjust the constraint capacity up or down as the average rate of actual demand shifts.

- **Buffer**: Define inventory in daily equivalent units. Equations to calculate the levels of buffer preload inventory were presented for a two-stage synchronized supply chain. The inventory investment was described in terms of preload inventory plus safety stock held at the push/pull boundary plus inventory risk pools for unique materials at the point of consumption. Overdrive the front end of the MPS to maintain the upside potential for throughput, and adjust node inventory up or down as the average rate of actual demand shifts.

- **Rope**: Pull to customer demand. Broadcast demand daily throughout the supply chain in a way that eliminates serial communications and delay, thereby defeating the bullwhip effect. Let the system constraint trading partner manage order backlog.

- **Performance measures**: A new description of equivalent throughput and total system inventory as two global performance measures was presented as a primary means of keeping a synchronized supply chain in alignment.

### REFERENCES


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**About the Author**

WILLIAM T. WALKER, CFPIM, CIRM, is a Supply Chain Architect. He spent over 30 years working both sides of the interface between supply chain management and new product development for Hewlett-Packard, now Agilent Technologies. He is accomplished in developing and optimizing international supply chains, has firsthand experience in worldwide product transfer logistics, and has personally developed successful new products. He is a Logistics Forum 2000 “Top 20 Logistics Executive” award winner. Mr. Walker co-developed the principles of supply chain management taught by APICS and is a co-author of the book *Supply Chain Management: Principles and Techniques for the Practitioner*. Mr. Walker is a past president of the APICS Educational and Research Foundation, where he collaborated on setting education strategy; and a past APICS Vice President of Education-Specific Industry Groups, where he had oversight responsibility for education developed for Aerospace and Defense, Process Industry, Repetitive, Remanufacturing, Small Manufacturing, and Textile/Apparel SIGs. He is APICS certified at the Fellow level, and holds BSEE and MSIE degrees from Lehigh University. He can be reached at billwalker@primeisp.net.
The practical application of Eli Goldratt's drum-buffer-rope TOC concepts to synchronize the supply chain resulted in excellent delivery performance for a medium investment in capacity, inventory, and information management. The supply chain redesign objective was accomplished, and synchronization was sustained during many months of volatile demand. Implementing Drum-Buffer-Rope in your production planning. Share. Put simply, Drum-Buffer-Rope (DBR) details a work schedule for the constraint (Drum), buffering the constraint so that it is never starved (Buffer), and setting a release mechanism to ensure that work gets released into the system at the right time (Rope). DBR is the production application of the theory of constraints management philosophy. The Drum is a schedule for the constraint, with the constraint being defined as the weakest link in the production line. The Buffer is the time provided for parts to reach the protected areas. (The protected areas are the Drum, the due dates and the assemblies of constraint parts with non-constraint parts.)