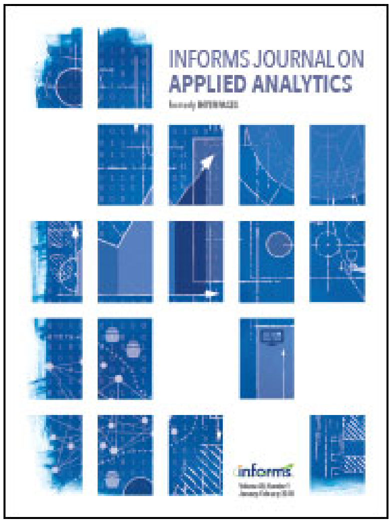

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Optimizing Inventory Levels Within Intel's Channel Supply Demand Operations

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Intel's Channel Supply Demand Operations (CSDO) organization is responsible for satisfying the boxed processor demands of Intel's vast customer network of distributors, resellers, dealers, and system integrators. In 2005, CSDO began a multiechelon inventory optimization (MEIO) project to improve its efficiency and effectiveness by optimizing inventory levels and locations across CSDO's end-to-end supply chain. This paper describes the project plan, workflows, and results. One year after implementation, total inventory levels were reduced by more than 11 percent; in addition, service levels of products modeled using the MEIO process were eight points higher than products not modeled using this process. The MEIO process continues to be in place at Intel and has resulted in sustained reductions in inventory levels, average service levels exceeding 90 percent, and more than an order-of-magnitude reduction in the number of expedites.

Key words: multiechelon inventory optimization; supply chain application.
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Founded in 1968, Intel introduced the world's first microprocessor in 1971. Today, it is the world's largest chip maker and a leading manufacturer of computer, networking, and communications products. Intel employs more than 80,000 people worldwide and produces more than 10 million chips each week. Although it sells microprocessors directly to the largest computer manufacturers, such as Dell, Hewlett Packard, and Lenovo, its Channel Supply Demand Operations (CSDO) organization is responsible for satisfying the branded boxed CPU demands of Intel's vast customer network of distributors, resellers, dealers, and local integrators. Intel's boxed processor shipment volume represents approximately 20 percent of its total CPU shipments.

In 2005, CSDO began a multiechelon inventory optimization (MEIO) project to improve the efficiency and effectiveness of its end-to-end supply chain. This paper describes the CSDO supply chain, the MEIO project, and the project's sustained results.

CSDO Supply Chain Overview

The CSDO supply chain begins after wafer fabrication and assembly-test factories have completed the production of finished microprocessors. Therefore, CSDO is managing a series of boxing and distribution activities in the supply chain. At any given point in time, CSDO sells 100–150 stock-keeping units (SKUs). SKUs are differentiated by microprocessor characteristics and are targeted to the desktop, workstation, laptop, and server markets with appropriate execution speed, power consumption, and multipin packaging for those markets.

To produce finished SKUs, a three-echelon supply chain (CW1, CW2, and CW3) transforms the finished microprocessors and converts them to saleable products (see Figure 1). The first echelon, CW1, represents finished microprocessor inventory at various assembly-test factory warehouses. At CW1, the microprocessors have completed all microprocessor

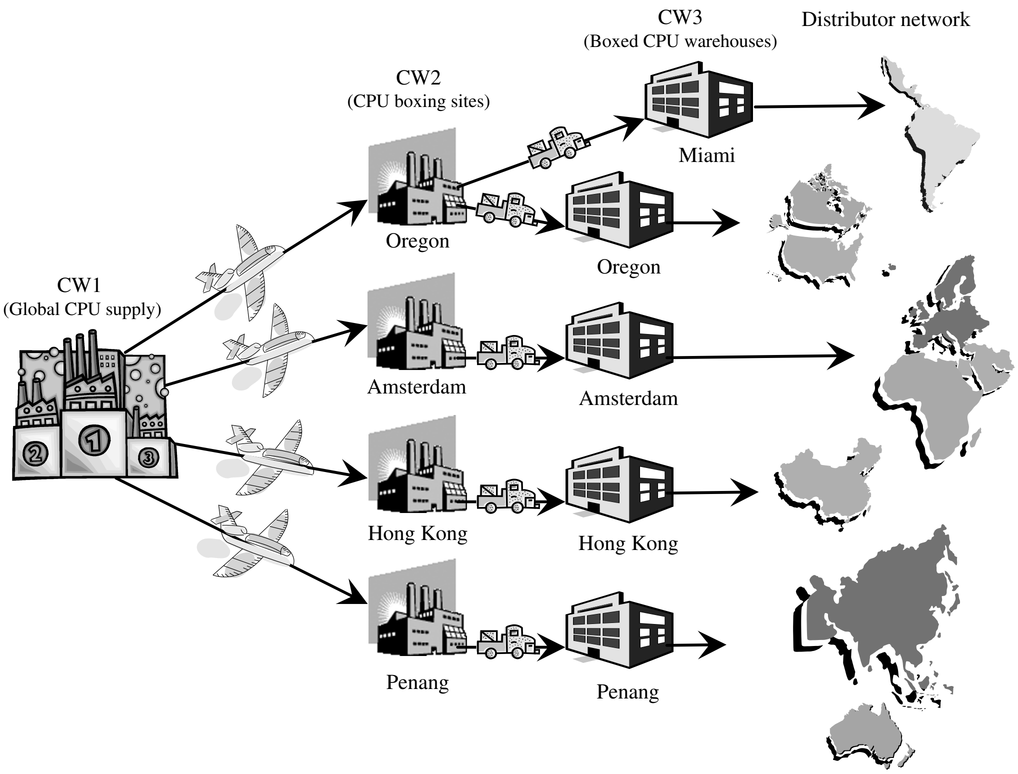

Figure 1: Intel's CSDO's boxing and distribution activities span three echelons.

fabrication steps and are in trays, which are organized by package type and speed. Processors ship from CW1 to one of four CW2 "boxing" sites, which kit the processors with cooling solutions (e.g., fan, heat sink) and place them in retail boxes and distribution containers. Such boxing sites are typically subcontracted companies that ship the boxed products to nearby Intel CW3 finished-goods warehouses where they are used to fulfill customer orders. Channel customers range in size and need; they are mostly low-volume computer manufacturers and electronics retailers.

MEIO Project Overview

The goal of the MEIO project team was to scientifically calculate optimal inventory targets across the three-echelon supply chain to ensure that CSDO's inventory investment would meet service-level objectives at minimum cost. The project sought to integrate the inventory targets into Intel's structured sales and operations planning process beginning in the fourth quarter of 2005.

The project's implementation process comprised four steps: (1) educating the organization on the need to solve this problem; (2) buying or building a multiechelon inventory optimization tool to provide the technological foundation for the solution; (3) developing sustainable processes and work flows, including system integration; and (4) developing and tracking metrics to ensure that the projected benefits from optimizing inventory targets were realized and quantified.

Step 1: *Supply Chain Education*. Intel's wafer fabrication plants cost more than $3 billion to build. The company has developed substantial expertise in maximizing the efficiency of these plants and has focused significant attention on efforts to improve throughput time and increase yields. The MEIO team realized that it was critical to augment Intel's "capacity mindset," which emphasized maximizing plant utilization, with a "supply chain mindset," which optimized the flow of material across the echelons of the supply chain. Managing this mindset change is harder than it sounds. A supply chain mindset stops wafer production starts if all orders and inventory targets are met. However, a decision to halt or delay wafer starts lowers capacity utilization—a closely watched metric for a multibillion-dollar plant. To resolve the difference between a capacity and supply chain mindset, the team had to show that a hierarchy of planning problems exists; moreover, it wanted to demonstrate that even after a company has made capacity decisions, it could save (or avoid) tens of millions of dollars in inventory costs by properly setting inventory targets. Although inventory costs are not the same order of magnitude as capacity acquisition and allocation costs, inventory costs are still significant and can be controlled after the plant capacity decisions have been made. Thus, rather than competing with capacity decisions, inventory optimization augments capacity planning by more cost-effectively allocating production capacity to the right products. Accepting this reasoning was a key step in the MEIO project implementation because it provided a justification for pursuing this initiative.

After establishing the importance of managing inventory, the team needed to demonstrate why multiechelon inventory optimization techniques were necessary to apply to this problem. Although many factors determine inventory requirements (including service level, lead times, supply variability, and demand variability), Intel's strong engineering culture required the team to focus on the problem's primary driver. At Intel, demand variability is the greatest source of uncertainty in the supply chain; product life cycles are relatively short—new products are introduced with great frequency. Managing product transitions is a particular challenge that exacerbates demand forecast error. Frequent transitions also make it hard to measure a specific product's demand uncertainty in terms of historical forecast error. Customers also contribute to demand uncertainty by ordering supply they might not need, then changing or cancelling these orders at a later date.

Furthermore, Intel's supply chain incorporates several geographically dispersed stages. The cumulative lead time of the end-to-end supply chain does not support an assemble-to-order business model; therefore, inventories must be strategically positioned to satisfy demand in a timely fashion. The question of how much of which product to hold at various geographies and stages of the supply chain requires a trade-off between fast responsiveness to customer requests and low inventory-cost exposure. Inventory held upstream at CW1 incurs less cost and maintains greater flexibility in configuration and geographical demand fulfillment. Inventory held downstream in either CW2 or CW3 supports rapid response to customers but incurs more unit cost and increases the risk of being positioned incorrectly. MEIO models minimize total inventory investment across the supply chain by optimizing inventory levels subject to end-customer service-level requirements; the appendix includes the mathematical programming formulation of Intel's MEIO model.

By educating the broader organization about the value derived from MEIO and the inherent challenges in optimizing inventory in the supply chain, the team was able to build consensus that adding multiechelon inventory optimization was important.

Step 2: *Tool Selection*. Once it was established that MEIO was a vital ingredient to add to CSDO's overall planning process, the organization had to make the classic technology make-buy decision. MEIO was an established technology with vendors providing solutions in the problem domain. Intel chose to buy the technology and integrate it into its existing planning processes rather than build it in-house. Following a vendor evaluation process, Intel selected Optiant's PowerChain Inventory product as its MEIO tool. The MEIO engine in PowerChain Inventory uses dynamic programming to optimize inventory levels and locations across the supply chain; the appendix includes details of the MEIO formulation.

PowerChain Inventory models the supply chain as a network in which stages represent an activity where safety stock can be held. Arcs denote the bill-of-material relationships between stages. Figure 2 translates the geographical supply chain map in Figure 1 to a PowerChain Inventory SKU-location map for a single microprocessor.

Safety stock can be held at four locations in the CSDO supply chain: CW1, a CW2 location before boxing occurs, a CW2 location after boxing occurs, or in the regions at CW3 warehouses. Because safety stock must be held in the form of a specific SKU at a specific location, a microprocessor held before a boxing

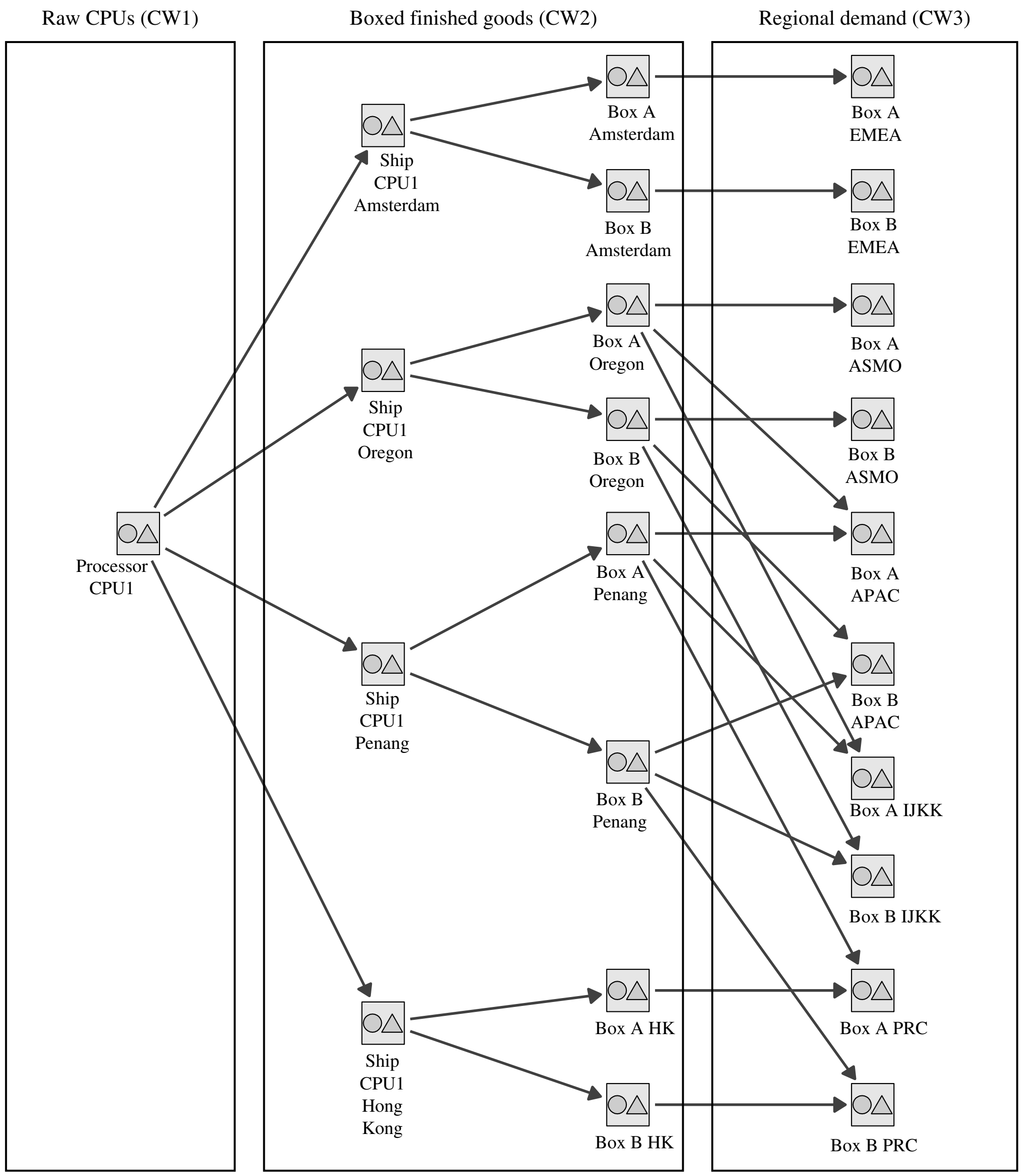

Figure 2: The CSDO supply chain consists of three warehouse echelons separated by transportation lanes and a finished boxing operation.

operation is denoted by one stage; however, after boxing it can be denoted by one of two stages because there are two types of boxing operations. For boxing operations that supply two geographies, a stage representing a boxed microprocessor has arcs to each CW3 location it supplies. In cases in which a CW3 stage is supplied by two CW2 stages, each arc has an arc multiplier that represents the fraction of demand satisfied by the boxing site. For a typical microprocessor that Intel sells, its resulting supply chain map in PowerChain Inventory has 23 stages and 28 arcs.

Arc multipliers are the only pieces of data associated with an arc. All other supply chain data are associated with a stage. All stages contain stage processing time, review-period length, replenishments per review, cost added, and holding-cost information.

Stages that are demand stages (CW3 stages in this model) also contain demand information: average demand, standard deviation of demand, and service-level inputs.

For CW1, the stage time is 30 days, which represents the time to receive completed units into CW1 inventory from wafer fabrication. Furthermore, CW1 maintains a review period of one month, with weekly replenishments; in this setting, although requests are made on the fabrication plants monthly, the plants resupply in weekly intervals. Because Intel uses air shipments between echelons, the time required to ship units from CW1 and place them into inventory before CW2 is less than one week. The boxing time at CW2 is another week. The shipment time to the CW3 finished goods warehouse is also a week. Both CW2 and CW3 operations run with a review period equal to one week.

To determine the average demand at CW3 stages, CSDO averages the next six weeks of forecasted demand. To calculate the standard deviation of demand, the one-month look-ahead forecast is compared to actual shipments in the current month. A key assumption is that standard deviation of demand, which is estimated by looking at historical data, will apply moving forward in time. Planners spend significant time validating this assumption. Prior to some events (e.g., price moves), planners perform sensitivity analysis on the standard deviation of demand to determine if a business case should be made for choosing different values for it.

Step 3: *Integrating MEIO into the Build Plan Process*. MEIO could only succeed if the tool was integrated into the processes and technologies CSDO already uses in its sales and operations planning (S&OP) process. The technological foundation of S&OP at CSDO is its internally developed build plan solver, BPS. BPS is a linear programming engine that resides within SAP's Advanced Planner and Optimizer (APO) module to reset the build plan on a weekly basis. The objective of BPS is to develop a build plan for the boxing factories to align boxed CPU supply with demand, leaving appropriate safety stock in the form of projected weekly ending-on-hand (EOH) inventory throughout the rolling 26-week horizon. Bean et al. (2005) provide details on Intel's BPS; Tian et al. (2011) include a more academic treatment of the integration of MEIO and BPS.

Figure 3 depicts the information flow between Optiant PowerChain Inventory (the MEIO tool) and BPS. Both tools share many pieces of data, which are pulled from a common data repository. Common data include the bill-of-materials routing, stage cost information, deterministic stage lead times, holding-cost rate, and average demand. As a general statement, MEIO-specific data characterize sources of variability in the problem, while BPS-specific data address capacity and material availability constraints. For example, MEIO-specific data include stage time variability, demand variability, supply variability, and service level targets. BPS-specific data include boxing factory throughput capacity, fan heat sink supply, and processor supply. BPS also has a set of inputs that attempt to resolve production infeasibilities; in their simplest form, these inputs include penalty costs; however, they can also include more direct demand and supply priorities that constrain certain products to be made in advance of other products.

The MEIO engine specifies the EOH inventory targets over the 26-week horizon. These targets are an additional input to BPS and are the link between the MEIO and BPS modules. Prior to the MEIO project, these EOH inventory targets were set as rules of thumb or derived by planners using tools developed in-house.

The primary output of BPS is a schedule of which processors the boxing lines should box in each week for the next 26 weeks. This triggers activities such as the movement of processors from CW1 to CW2 and the procurement of fans and heat sinks. BPS also generates a report that compares time-phased inventory positions to the EOH inventory targets for purposes of validating the build plan.

Metric Development

A project can only be judged against its metrics. Consistent with this philosophy, during the initial implementation in 2005, the MEIO team used the available data to establish two metrics to judge the project's success or failure: actual service level achieved and total inventory level. A third metric that captures the change in the number of change order requests (CORs) was added in 2006 when the required data became available.

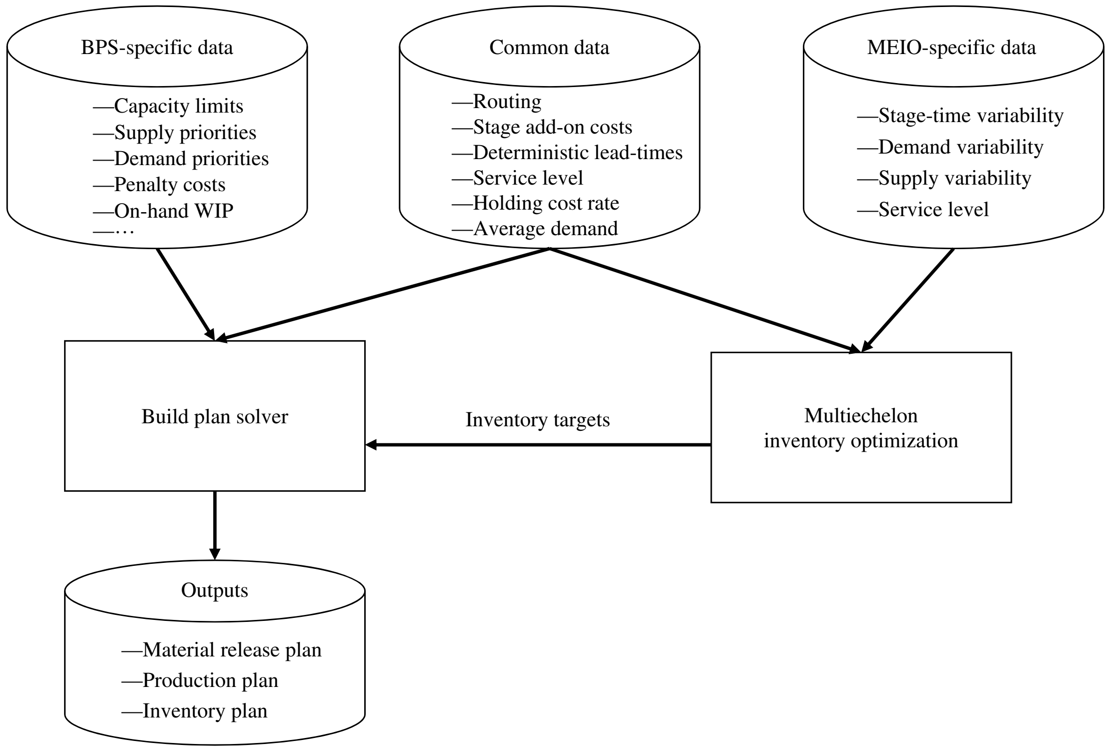

Figure 3: The information flow between Intel's build plan solver and multiechelon inventory engine requires both shared and unique data elements.

Inventory level is the most straightforward metric. It is the total dollar volume of inventory in the CSDO supply chain. Service level is more difficult to measure. Intel's service-level metric does not conform to a traditional Type I or Type II error found in a textbook; Type I measures order fill rate, whereas Type II measures volume fill rate. Instead, Intel measures first-order fill rate, which is the percentage of an order filled on the date the customer first asks for the product.

The dynamic market that CSDO serves generates tens of thousands of CORs each year. They are classified as regular CORs (customer change requests that can be accommodated within the customer's geography by utilizing finished-goods inventory at CW3 or initiating a box build utilizing CPU inventory at CW2) or escalated CORs (customer change requests that require the CSDO planners to consider CPU inventory at CW1 or go farther back into Intel's supply chain and negotiate with the fabrication and assembly-test plants to change their production schedules and/or allocations to CSDO to satisfy the altered customer demand). Given Intel's need to be responsive to customer requests and changing market conditions, CORs will never be entirely eliminated. However, regular CORs that can be resolved by a planner within his or her geography are preferable to escalated CORs, which necessitate a more disruptive intervention.

Three Obstacles Encountered in Integrating BPS and MEIO

From a process perspective, the team encountered three difficulties integrating MEIO and BPS. The team had to develop a process to parameterize service-level targets, determine which SKUs to model with the MEIO tool, and reconcile how to treat safety stock targets in BPS when capacity is constrained.

Setting Service Levels

Although Intel had always maintained service-level targets for each SKU, these targets become more significant in the presence of an MEIO tool because they serve as a primary model input for MEIO. In contrast, when only rules of thumb are used, service level is primarily used to measure against actual performance. CSDO's 150 active SKUs include new products ramping up, old products ramping down, and midlife products in volume production. The planning organization must manage this SKU portfolio by balancing both tactical near-term and strategic long-term revenue objectives. Newly introduced processors must be stocked sufficiently so that the products can grow to become tomorrow's high-volume sellers. Conversely, old products must be phased out in a manner that protects customers, transitions them to the next high-volume product, and leaves Intel with as little obsolete inventory as possible.

To bring clarity to this difficult portfolio allocation problem, CSDO partitions its SKUs into one of three categories: A, B, or C. This partitioning scheme is based on more than just current revenue. It takes into account future volume potential, revenue potential, and strategic value to Intel. At any point in time, 20–30 SKUs are A items, 40–60 are B items, and the remaining 50–75 are C items. By properly segmenting the SKUs, CSDO can develop service-level objectives appropriate for each classification.

Choosing SKUs to Model in an MEIO Tool

In theory all SKUs could be modeled by the MEIO tool; however, the team recognized that there are diminishing returns to modeling low-volume SKUs. Therefore, a SKU's volume dictated whether its safety stock targets were calculated by the MEIO engine. Products with more than 3,000 units of demand per month and 12,000 units per quarter were modeled in the MEIO tool. These products had the volume sufficient to forecast, and properly setting safety stock could significantly affect supply chain performance. The products represent 70–90 percent of CSDO's quarterly demand, and the volume thresholds are varied to ensure this range on a month-to-month basis. For products with demand between 300 and 3,000 units a month, safety stock targets were set with a rule of thumb equivalent to a specified week of inventory based on the SKU's A–B–C classification. For SKUs with demand less than 300 units a month or ramping down dramatically or completely within three months, safety stock was not held and the SKU was managed on a make-to-order basis.

Prioritizing Safety Stock Targets

When capacity constraints prevent entirely meeting the suggested safety stock targets generated by the MEIO tool, the build plan process must prioritize which safety stock targets should be satisfied. This is an iterative process that begins by constraining the MEIO tool to hold inventory only at certain stages in the supply chain. The team adopted a rule to prioritize safety stock targets at CW2 and CW3 over CW1.

This rule makes economic sense for Intel's objectives. First, inventory on hand has no value if it cannot satisfy customer demand. Having inventory at CW2 and CW3 allows Intel to satisfy demand off the shelf or through regular CORs. This lowers the total landed cost of providing supply, because it makes the process more predictable versus relying on expediting and the hidden costs expediting incurs. Second, holding inventory at CW2 and CW3 almost always requires less total inventory, albeit at a higher cost, than holding some inventory at these downstream locations and a decoupling inventory at CW1. This last result can be seen in the standard inventory equation, $z\sigma\sqrt{T}$, where z is the safety factor, σ is the standard deviation of demand, and T is the coverage time. For a three-stage serial line in which stage 1 feeds stage 2, which feeds stage 3, and the coverage time of stage i is T_i, then $z\sigma\sqrt{T_1} + z\sigma\sqrt{T_2} + z\sigma\sqrt{T_3} > z\sigma\sqrt{T_1 + T_2} + z\sigma\sqrt{T_3} > z\sigma\sqrt{T_1 + T_2 + T_3}$; the leftmost expression maintains a decoupling inventory at all three stages, the middle expression holds inventory only at stages 2 and 3, and the rightmost expression places a single decoupling inventory at stage 3. For more complex distribution networks, such as CSDO, demand pooling can offset this effect. Resolving this tension is precisely why the optimal inventory placement in a multiechelon supply chain requires an optimization model. However, for Intel's chains, it often requires less total inventory if only the downstream stages hold safety stock, albeit at a higher inventory cost. In a capacity-constrained environment, requiring less total inventory is more important than incurring less inventory cost.

Planners use this prioritization as a starting point and rely on more complex procedures if these techniques are insufficient to get below the capacity

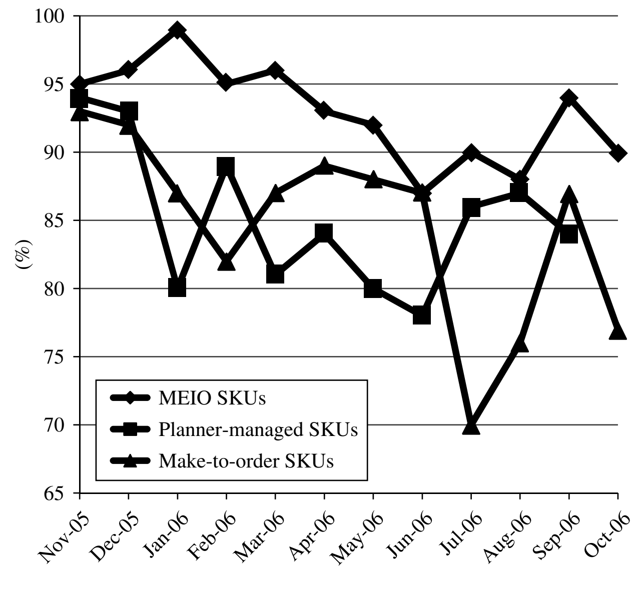

Figure 4: SKUs managed by the MEIO tool have significantly higher service levels (defined as first-order fill rate) than planner-managed SKUs.

constraint. Examples include pushing out delivery dates or, as a last resort, cutting orders.

Results

In the fourth quarter of 2005, the MEIO tool went live as an integrated component of the build plan process. Figure 4 reports the actual service levels (measured as first-order fill rate) attained for each class of managed SKUs beginning in November 2005. We refer to SKUs managed with the MEIO tool as part of the build plan process as MEIO SKUs. SKUs for which planners manually set and maintain inventory targets are classified as planner SKUs. The final set of SKUs are make-to-order SKUs. Intel does not maintain a safety stock target for these SKUs; however, the planners must plan their production quantities when necessary, and inventories for these SKUs arise when supply and demand are unbalanced.

SKUs planned by the MEIO tool consistently achieve higher service levels than the set of planner-managed or make-to-order SKUs. From November 2005 through December 2006, the MEIO-managed SKUs achieved an average service level that was eight points higher, in absolute terms, than planner-managed and make-to-order SKUs. Because the MEIO-managed and planner-managed SKUs have the same service-level targets, strong anecdotal evidence suggests that the modeling and management processes put in place are the primary reasons for the MEIO tool's success. Although product characteristics between the SKU sets could contribute to the discrepancy, the MEIO team has concluded that the primary difference is that the MEIO tool bases its inventory targets on variability, whereas planners tend to still manage targets based on average future demand coupled with their judgment of future business conditions. Furthermore, the planner-managed SKUs carried a higher average inventory, while achieving lower actual service levels.

In terms of inventory performance, Figure 5 presents total CSDO ending-inventory numbers at CW2 and CW3 for the three-month period prior to program launch in 2005 versus the corresponding three months in 2006.

During this three-month period, Intel managed several significant product transitions. It began shipping the first quad-core microprocessors in volume, and it shifted volume production to a 65-nanometer technology. Against this backdrop, within one year of implementation, CSDO had reduced inventory across CW2 and CW3 locations by 11 percent—from 4.5 weeks of inventory (WOI) to 4 WOI at these two echelons in the supply chain.

By properly deploying inventory across the channel, and in particular holding inventory downstream

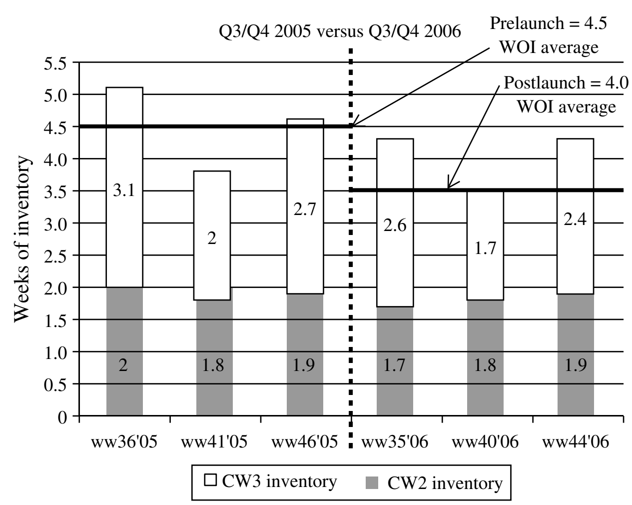

Figure 5: One year after implementation, total inventory levels were 11 percent lower.

in times of constrained capacity, CORs could be satisfied directly at CW3, or boxing inventory at CW2 and subsequently moving it to the appropriate CW3 location, versus requiring an escalated COR and then expediting the material to the customer. Proper safety stock management reduces the need for COR escalations and expedites Intel's responsiveness to dynamic customer demands.

Figure 6 displays CSDO's total inventory and COR performance during the first 30 weeks of 2008. It shows two COR metrics: change requests that can be met in one day, labeled on the figure as Responsiveness (yes in 1 day), and change requests that can be met within one week, labeled on the figure as Responsiveness (yes in 1 week).

Figure 6 clearly shows that total inventory levels have continued declining at a steady, albeit modest rate; service, in the form of successfully satisfying change requests in one or seven days, has significantly increased. There is a trade-off between inventory and service, and CSDO has chosen to maintain this right-sized aggregate level of inventory while improving service performance. Furthermore, the absolute number of escalated CORs has decreased by more than an order of magnitude; fewer than 1,000 escalated CORs are generated per week. Achieving and sustaining these kinds of improvements over a three-year period would not be possible without the structured process and tool implemented in the MEIO project.

Project Learnings

At Intel, one innovative aspect of the project was the team's clear statement of and dedication to continuous improvement principles from the project's onset. Although these principles are easy to state, the practice of these principles ensured that the project stayed within scope, finished on time and under budget, and delivered meaningful results. The four principles are as follows:

Keep models and processes simple. A majority of the benefit can be obtained by developing a consistent and straightforward process. The supply chain

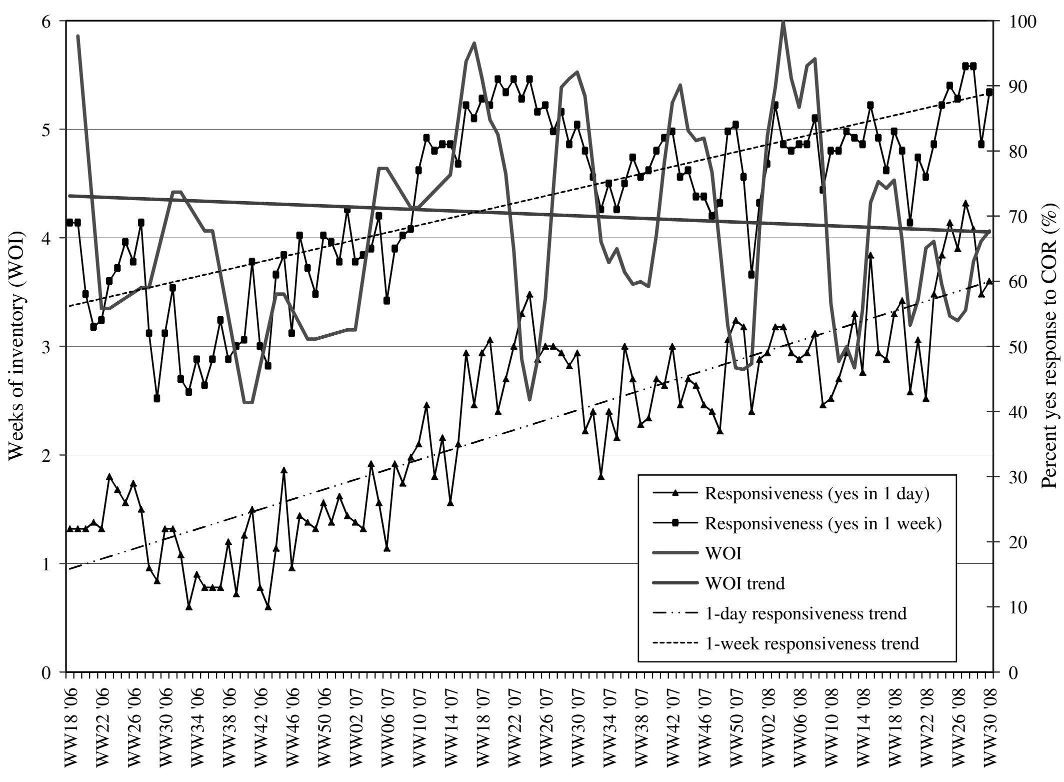

Figure 6: CSDO inventory levels have modestly decreased while service (as measured by satisfied change order requests) have significantly increased over the past two years.

models and new business practices must be easy to create, explain, validate, and maintain. For a company with as strong an engineering culture as Intel has, keeping things simple is always a challenge.

Make things better now. There is plenty of time to pursue perfection through continuous improvement effort after initial implementation. Project trade-offs, including characterizing the data required for each model, were based on the desire to move in the right direction, knowing there is always room for improvement in the future.

Implement in a phased manner. The team consciously set out to initially model the set of SKUs that has the most influence on near-time costs and revenue—not all the SKUs in the business.

Be clear about what success is. To be judged successful, the project had to deliver improved responsiveness to customer requests with a lower aggregate inventory investment.

Project Summary

By following the project guidelines, the team was able to implement the MEIO tool on time and achieve the projected savings established at the outset. Although the performance results were significant, the project also resulted in organizational learnings. First, because it provided a scientific approach to defining box processor safety stock targets, the entire CPU supply chain gained increased confidence in the numeric targets provided. This reduced second-guessing of the numbers by different organizations and created a more stable demand signal across the company. Second, safety stock targets could now be optimized by SKU by location, avoiding multiple manual calculations and standardizing planning approaches across the regions. Finally, this project demonstrated the importance of correctly modeling variability in the supply chain. Augmenting Intel's capacity mindset, which focused exclusively on factory utilization, with a supply chain mindset, which focused on lowest landed cost across the supply chain, was an important paradigm shift within the company.

Appendix

The guaranteed service (GS) model of inventory placement forms the mathematical underpinnings of the MEIO tool. Graves and Willems (2000) describe the basic version of this model; the CSDO problem contains advanced functionality, including review periods, as Bossert and Willems (2007) describe, and acyclic network structures, as Humair and Willems (2011) discuss. This appendix provides an overview of the standard GS formulation.

GS Model Formulation

The standard GS model can be formulated as the following mathematical program **P**:

$$
\begin{aligned}
\mathbf{P} \quad \min \quad & \sum_{j=1}^{|N|} h_j \cdot [D_j(SI_j + T_j - S_j) - (SI_j + T_j - S_j)\cdot \mu_j] \\
\text{s.t.} \quad & S_j - SI_j \le T_j \quad \forall\, j \in N, \\
& SI_j - S_i \ge 0 \quad \forall\,(i, j) \in A, \\
& S_j \le s_j \quad \forall\, j\colon \nexists\, k \in N \mid (j,k) \in A, \\
& S_j, SI_j \ge 0, \text{ integral} \quad \forall\, j \in N,
\end{aligned}
$$

where N is the number of stages in the supply chain, h_j is stage j's holding cost, T_j is stage j's lead time, $D_j(\cdot)$ is stage j's demand bound, s_j is a bound on the outbound service time a demand stage j can quote, and μ_j is the mean demand received per period by stage j. The decision variables are the service times S_j and SI_j, which affect inventory levels and locations. S_j is the outgoing service time stage j quotes it downstream-adjacent stages. SI_j is the incoming service time to stage j; it is the maximum outgoing service time quoted to stage j by its upstream-adjacent stages. The first set of constraints restricts the outgoing service time at a stage to be no greater than the stage's incoming service time plus stage lead time. The second set of constraints enforces the definition of inbound service time to stage j as the largest outgoing service time quoted to stage j by its immediate-predecessor stages. The third set of constraints restricts outgoing service time to be less than or equal to the user-defined limits and the final set of constraints enforces nonnegative and integrality on the service times.

The strength of the formulation in **P** is that it allows us to cast a nonlinear integer stochastic program as a deterministic nonlinear program. With this reformulation, established dynamic programming techniques can be used to efficiently solve large-scale problems to optimality. Graves and Willems (2000) describe how to solve **P** in the case of spanning tree networks; Humair and Willems (2011) expand the class of networks that can be solved to encompass general acyclic networks with arbitrary stage cost functions; review periods are an example of a modeling enhancement that produces nonconcave stage costs.

References

Bean JW, Devpura A, O'Brien M, Shirodkar S (2005) Optimizing supply chain planning. *Intel Tech. J.* 9(3):223–231.

Bossert JM, Willems SP (2007) A periodic review modeling approach for guaranteed service supply chains. *Interfaces* 37(5):420–435.

Graves SC, Willems SP (2000) Optimizing strategic safety stock placement in supply chains. *Manufacturing Service Oper. Management* 2(1):68–83.

Humair S, Willems SP (2011) Optimizing strategic safety stock placement in general acyclic networks. *Oper. Res.* 59(3):781–787.

Tian F, Willems SP, Kempf KG (2011) An iterative approach to item-level tactical production and inventory planning. *Internat. J. Production Econom.* 133(1):439–450.

Frank Jones, Vice President, Technology and Manufacturing Group, General Manager, Customer Fulfillment, Planning and Logistics at Intel Corporation, writes: "I write this to verify that Brian Wieland, Pat Mastrantonio, and Karl Kempf of Intel Corporation and Sean Willems of Boston University did conduct the work reported in "Optimizing Inventory Levels Within Intel's Channel Supply Demand Operations." Given the volume and dollar value of Intel's boxed CPU business and corresponding inventory, deriving inventory targets in a more structured and objective manner was critical to standardizing and improving box inventory management required to meet the goal of improving customer service levels with lower aggregate inventory investment.

"Prior to implementing a multi-echelon inventory optimization (MEIO) inventory optimization tool and business process, CSDO had a non-standardized "weeks of inventory" (WOI) approach for setting inventory targets based on individual planner experience and judgment. CSDO had no standardized, integrated strategy that incorporated demand variability, the greatest source of uncertainty in the boxed CPU supply chain. The MEIO project team implemented a tool and process which delivers scientifically derived inventory targets across the three-echelon boxed CPU supply chain to achieve desired service levels at the minimum inventory investment. The implementation of the MEIO tool and process resulted in reduced overall inventory investment with higher service levels compared to products not modeled in the MEIO tool as indicated by key business metrics. As Intel's focus has evolved to be more customer-centric, MEIO tool and process refinements allowed CSDO to improve model performance, resulting in higher rates of responsiveness to customer change order requests through appropriate inventory staging strategies.

"The implementation of the MEIO tool/process was the first use of statistically derived inventory targets for Intel Architecture processors and represented a breakthrough in challenging existing paradigms. By following project guidelines of simplification, immediate incremental improvement, phased implementation and clearly defined success criteria, the MEIO project team was able to implement MEIO on time and achieve the anticipated results. Through key learnings and growing acceptance of MEIO methodologies, the use of statistically derived inventory optimization strategies is now expanding beyond the boxed CPU supply chain at Intel."