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Capacitated MRP in the Process Industries: Practice and Theory in Consumer Goods Manufacturing

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At the past two APICS International conferences, we presented papers on the changing nature of manufacturing within the process industries. The paper for the 1995 APICS International conference (Schuster and Allen, 1995) featured a new framework for production planning and control in the process industries. In 1996, we presented a structure for supply chain management in the consumer goods sector of the process industries (Schuster, D'Itri, and Allen, 1996). This paper included discussions of each link of the supply chain along with real world examples drawn from Welch's, Inc.

For the 1997 International Conference, our thoughts now turn to an emerging area within the supply chain called Capacitated Material Requirements Planning (CMRP). In the past ten years, the process industries found great advantage by applying finite planning ideas to master production scheduling. However, having capacity-feasible production schedules alone does not ensure smooth operations. Process-oriented firms also must procure large amounts of raw materials from a vast network of vendors. An increasing number of process-oriented firms report problems with traditional, infinite capacity MRP when it comes to planning the purchase and conversion of raw materials in support of production plans. Hence, the objective of this paper involves the research and development of CMRP in the process industries. As with our previous work, we discuss CMRP in the context of theory, as well as practical application.

The development of CMRP for the process industries is one of the three applied research objectives we have established at the Center for Process Manufacturing. Located on the campus of Penn State Erie, The Behrend College, the Center became active in 1992 and has five associates who focus their research efforts on the process industries. By 1993, the Center had established a formal partnership between APICS, Penn State and industry, with the goal of transferring applied research from academia to industry. Besides CMRP, the Center also conducts applied research in Continuous Replenishment Systems (CRP) and Finite Planning (FP). At the Center for Process Manufacturing, we strive to bring the ideas of mathematics to practice, and to promote the general use of models in business problem solving. APICS has published some of the applied research conducted by members of the Center (see Allen, 1990; Schuster and Finch, 1990; Allen and Schuster 1994; Allen, Martin, and Schuster, 1997).

THE ISSUES OF CMRP

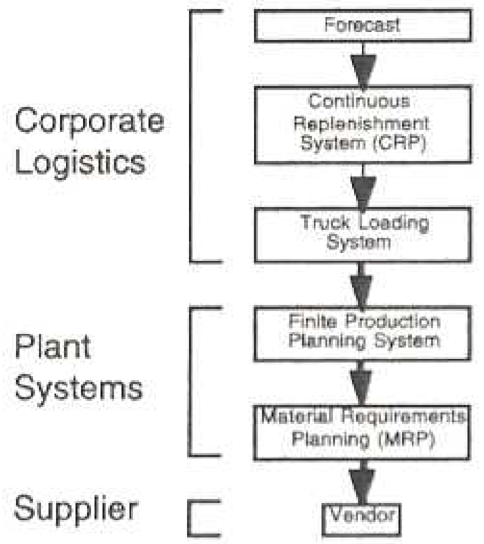
Whether based upon dependent or independent demand, the calculation of lot sizes follows a similar line of logic. In all lot sizing methods there is a tradeoff between set-up costs and inventory carrying costs. Some lot sizing methods perform this cost trade-off using complex calculations while other methods involve simple calculations with implied assumptions concerning the optimal lot size. The traditional methods, dating from the mid-1950s to the mid-1970s, calculate the optimal lot size with no consideration given to capacity. Wagner and Whitin (1958) published groundbreaking research on optimal lot sizing, with infinite capacity and dynamic demand, several years before the first MRP implementation. Since the early 1980s, researchers have developed some practical methods to determine the optimal lot size based on capacity constraints.

The objective of CMRP then becomes calculation of the optimal lot size for dependent demand given a material or processing capacity constraint. For the modern process-oriented firm, the ultimate source of the dependent demand is a master production schedule (MPS) for end items. The MPS should consider constraints such as production line capacity. Often, the MPS becomes disrupted if lower-level raw material or work in process (WIP) is not available at the proper time. This causes elevated cost and poor customer service. In the case of raw materials, a typical capacity constraint may involve the ability of a vendor to supply a manufacturing plant at a specified rate. In the case of an internal manufacturing process, the capacity constraint might involve the sequencing of lower-level, raw material processing involving a critical piece of machinery. With each case, an extreme disturbance to the MPS can occur if dependent demand lot sizing calculations assume infinite capacity. CMRP serves an important role in the supply chain by reducing the potential for disruption to the MPS. However, CMRP also raises four important issues concerning practical implementation:

- *Multilevel versus Single Level*—For process-oriented firms that have deep bills-of-material (BOM), CMRP must optimize cost while meeting capacity constraints across **all** levels of the BOM. This offers a very complex problem with few, if any, practical solutions. Optimization of cost while meeting capacity constraints becomes a much more tractable problem when considering only a single level of the BOM. However, this could lead to local optimal solutions in cases where a deep BOM exists (see Toelle, 1996).
- *Large-Scale CMRP versus Small-Scale CMRP*—Proposed large-scale systems for CMRP usually include massive use of mathematical programming, along with special techniques to gain a solution in a reasonable amount of time. This approach requires a great deal of knowledge to make CMRP work. The alternative involves selective, small-scale application of mathematical programming and heuristics to **existing**, infinite capacity MRP systems. This choice has the advantage of reduced cost of implementation and decreased complexity.
- *WIP Lot Sizing versus Raw Material Lot Sizing*—Some researchers feel that WIP and raw materials require different lot sizing methods to deal with the divergent internal and external environments experienced by process-oriented firms. Practitioners commonly use a single lot sizing method for WIP and raw materials. This may lead to inappropriate lot sizing solutions.
- *MultiPlant versus Single Plant*—Many process-oriented firms have a network of manufacturing plants that depend on each other for raw materials and WIP. This increases the complexity of CMRP and raises the question of a "third model" approach to guide transfers of critical WIP and raw materials between plants based on capacity constraints and need.

These four critical issues raise serious questions concerning the viability of CMRP in practice. A recent survey shows practitioners rank capacity management a very high business priority (Berry and Lancaster, 1992), yet, another survey reports that practitioners most commonly use the simplest MRP lot sizing techniques (Haddock and Hubicki, 1989). This is despite several studies showing the simplest lot sizing techniques are poor performers in optimizing cost on a single-level and multilevel basis (Choi, Malstrom, and Tsai, 1988; Nydick and Weiss, 1989; and Coleman,

Figure 1. The supply chain model.



1992). All these studies look at lot sizing for dependent demand under conditions of infinite capacity.

With the apparent underutilization of lot sizing techniques in current, infinite capacity MRP systems, why should we suppose CMRP as a viable planning method? Two answers exist for this question.

First, the survey conducted by Haddock and Hubicki makes no mention concerning the proportion of process-oriented firms compared to the number of total replies. Few of the software companies that participated in the lot sizing survey appear to have roots in the process industries. For this reason, results favor the current condition in discrete manufacturing rather than a fair appraisal of lot sizing in the process industries. Taylor and Bolander (1994) argue the process industries rejected traditional MRP logic in favor of other methods that use the process structure to guide scheduling calculations. If this is true, the survey results on lot sizing in discrete manufacturing may not apply to the process industries. Common observation shows that dependent demand lot sizing with capacity constraints takes on great importance in the process industries. One need only work a short time in a fluid processing plant to know that free tank space forms an important constraint when deciding what lot size to produce.

A second answer to the question of CMRP viability involves the business environment experienced by process-oriented firms. During the 1996 APICS International conference (Schuster, D'Itri, and Allen, 1996), we discussed the importance of an integrated supply chain, with electronic links spanning from the customer to suppliers of basic raw materials. Figure 1 shows the basic supply chain model we put forth. In such a system it becomes important to consider finite capacity at each link of the supply chain. Since MRP serves as an important business function of process-oriented firms, it must include capacity constraints to promote a smooth flow of materials.

With a little motivation, process-oriented firms can mold selective aspects CMRP into a practical tool for dependent demand lot sizing. This requires an honest analysis of the business environment, along with a desire to overcome the four implementation issues that limit the use of CMRP among practitioners. We now discuss aspects of process-oriented manufacturing that allows for practical implementation of CMRP.

TRAITS OF PROCESS MANUFACTURING

When studying the process industries, it becomes clear that a wide range of manufacturing environments exists. Most agree that process-oriented manufacturing differs from discrete manufacturing in important ways. However, differences also exist between various segments within the process industries. This limits opportunities to develop universal models of manufacturing planning and control systems that cut across all process industry segments.

In this article, we choose to focus attention on the consumer goods (CG) segment of the process industries. This segment represents a large part of the U.S. economy and highlights some interesting problems in planning and control. Effective solutions for the CG segment also find application in other segments of the process industries.

Intense competition and high expectations for customer service dominate the business environment of CG firms. Demand often varies with time as promotional activity causes wide swings in week-to-week shipments of finished goods. Unexpected events sometimes trigger surges in demand. As an example, a recent research study reported the benefits of purple grape juice in prevention of heart disease. This caused a huge increase in demand for Welch's products. The sudden increase in demand placed a great deal of pressure on Welch's planning and logistics systems. Above all, it is important for CG firms to maintain a steady stream of products to the market place regardless of sudden changes in demand.

To support dynamic demand, CG manufacturers need systems that account for capacity constraints at all levels of the production planning and control system. This ambitious goal remains elusive for most GC firms. However, one characteristic of CG manufacturing sets it apart from discrete-oriented firms. The flat bill of material structure typical of CG firms allows a greater chance of surmounting the four critical issues of CMRP implementation:

- With flat bill of material structures, CG firms can apply single-level CMRP with reduced chance of finding local optimal solutions.
- CG firms can modify existing, infinite capacity MRP systems by the strategic use of heuristics to optimize cost while meeting capacity constraints, eliminating the need to employ large-scale CMRP.
- Because of flat bills of material, CG firms have fewer levels that require critical lot sizing decisions; lot sizing can become more specific rather than using a single lot sizing method for both WIP and raw material purchasing.
- Flat bills of material help simplify the coordination of material flows in multiplant situations. This allows for specialized solutions unique to multiplant, CMRP situations.

Finch and Cox (1987) note in their study of process-oriented firms that product families often take on a "V" structure. In this case, a product family has one or very few raw materials but a wide range of end products. The V structure occurs frequently in all segments of the process industries. Finch and Cox (1989) also observe that V structure influences the nature of buffers required to keep bottleneck work centers at full capacity. This implies the need for a constraint based planning system to schedule work centers. The combination of a V structure and flat BOM offers CG firms a great opportunity to apply CMRP.

Before review of some applications of CMRP, we turn our attention to the CMRP literature documented by APICS and other organizations interested in operations management. This discussion offers a backdrop to the applications of CMRP at Welch's, Inc.

COMMENTARY ON THE LITERATURE OF CMRP

The literature documents three approaches to solving the CMRP problem. It is impossible to cover all the writing on MRP and lot sizing. However, it appears CMRP solutions fall into the following categories: mathematical programming based, heuristic based, and the theory of constraints (TOC).

CMRP and Mathematical Programming

Early efforts to address lot sizing with limited capacity trace to Dzielinski and Gomory (1965) with later expansion by Nahmias (1989). Their work involves the use of a "sifter" to determine the best tradeoff between inventory carrying cost and setup cost while still meeting capacity constraints. Schuster and Allen (1997) demonstrate this technique for production lot sizing using data from Welch's. The method applies to either dependent or independent demand lot sizing with limited capacity. In practice, the "sifter" method requires specialized knowledge of integer programming. No documented application of this method exists in practice. However, the "sifter" does provide an idea of the complexity involved in finding optimal solutions to capacitated lot sizing problems.

The work of Dzielinski and Gomory deals with single-level lot sizing. As noted, the single-level approach may yield a local optimum in situations where there are many levels to the bill of material. Other authors attempt to find multilevel, optimal solutions. McLaren (1977) provides a well-referenced example. This work uses integer programming but assumes infinite capacity. For large problems, it becomes difficult to find solutions using integer programming. Again, as with the sifter, it is hard to put McLaren's formulation into practice.

Other authors currently apply mathematical programming to multilevel, capacitated lot sizing problems. Most notable is the work of Leachman, Benson, Liu and Raar (1996). They report application of linear programming at Harris Corporation—Semiconductor Sector as a replacement for the previous, infinite capacity MRP system. This extensive project required several years to complete, but provided solid results in raising on-time deliveries from 75 to 95 percent without increasing inventory.

Mathematical programming provides great potential for CMRP. Wider application of this method depends on increased computing power and the ability to solve large-scale mathematical programming models quickly. The level of specialized knowledge required to operate these systems may limit their overall use in industry for the immediate future.

CMRP and Heuristics

Where mathematical programming provides optimal solutions for capacitated lot sizing using complex algorithms, heuristics find solutions with "rules of thumb" that come close to optimal solutions. The advantages of heuristics lie in simplicity of concept and speed of solution. Certain types of mathematical programming formulations can take a long time to reach the one best, optimal solution. On the other hand, heuristics converge quickly to a solution that is close to, or even may match, the optimal solution.

The risk with heuristics involves the ability to provide "good" solutions over a wide range of conditions. A heuristic may perform well under certain conditions, but may give very poor answers under another set of conditions. There is no way to predict the performance of heuristics other than through intensive testing.

Dixon and Silver (1981) provided early work on a heuristic for single-level lot sizing with capacity constraints. Their work links to the infinite capacity lot sizing method developed by Silver and Meal (1973). The Silver-Meal heuristic performs well under a number of different conditions and is simple to use.

Allen, Martin, and Schuster (1997) improve upon the Dixon-Silver heuristic by adding setup time and by using an Excel spreadsheet combined with visual basic to calculate capacitated lot sizes for independent demand. They provide sophisticated test data on how well the heuristic performs over a wide range of conditions. This paper also provides some solid references from European researchers who deal with capacitated lot sizing. The approach taken by Allen, Martin, and Schuster applies equally well to dependent demand, lot sizing situations.

CMRP may only become a reality through the wise application of heuristics to determine proper lot sizes. The promise of rapid solutions gives solid reason to continue research in the area of lot sizing heuristics. However, heuristics do not perform equally well under all conditions of demand. The practitioner should apply heuristics in those cases where previous testing provides confidence of success.

CMRP and Theory of Constraints

The decade of the 1980s saw the rise of the theory of constraints (TOC) as an innovative approach to scheduling. Jacobs (1983) details an early review of optimized production technology (OPT), a software system based on TOC principles. At the heart of TOC lies the concept of drum-buffer-rope (DBR) scheduling, which attempts to maximize flow through plant bottlenecks. Reimer (1991) concisely describes DBR scheduling in the following passage:

"Generating a drum is the finite scheduling of the system capacity constraint resource, the CCR. Buffer management is the time protection for the CCR against any kind of disruption. The rope is the timely release of raw material into the system, which is tied to the size of the buffer."

DBR scheduling mostly applies to job shops where production flows through a number of work centers before completion (for an example see Spencer, 1988). The flow concept of DBR scheduling does not completely approximate situations encountered by the process industries. For this reason it remains unclear exactly how to apply TOC. A survey of APICS literature reveals few, if any, true applications of TOC in the process industries. However, the literature does list several articles that analyze the relationship between TOC and MRP (see Plenert and Best, 1986; Swann, 1986; Vollmann, 1986; Spencer, 1991), and the relationship between TOC and JIT (see Fawcett and Pearson, 1991; Cook, 1994). Spencer and Cox (1995) discuss master scheduling in a TOC environment and Chakravarty (1996) shows a case study of DBR implementation. The interested reader should reference Finch and Luebbe (1995) for a balanced review of TOC.

We continue our discussion of CMRP by describing some applications in CG manufacturing. The first example deals with a multiplant, CMRP problem involving capacity and material constraints. For this example we use linear programming to find a solution. The second example entails a single-level, CMRP lot sizing problem for a critical piece of machinery. This example highlights the use of a heuristic to find a solution.

RAW MATERIAL MANAGEMENT AT WELCH'S

Every year, farmers deliver over 250,000 tons of grapes to Welch's for pressing into juice. Welch's stores the grape juice in large refrigerated tanks for year-round use in producing jams, jellies, concentrate, and bottled juice. "Tons" represents the base unit of planning. A "ton" equals the amount of juice obtained from pressing one ton of grapes. During the year, Welch's must make decisions on how to best use the grape crop. Typical decisions include:

- recipes to use for major product groups
- transfer of grape juice between plants
- control of carryover to ensure enough room for the next crop
- financial impact of recipe and transfer decisions
- the mode of transportation (rail or truck) for transfers of juice between plants.

Welch's has a refined cost accounting system that calculates requirements for Concord and Niagara grape juice by month, in tons. The system accounts for the recovery loss and cost of converting Concord and Niagara grapes into finished product. In June 1996, the company implemented a fully integrated material requirements planning (MRP) system that calculates time-phased requirements for all components needed to manufacture finished products. The new MRP system takes advantage of relational database information technology and operates in real time rather than batch mode. The new, mini-computer based, cost accounting and MRP systems also allow for extraction of data to computer spreadsheets. Yet both these systems have two major drawbacks: they assume infinite capacity and do not consider operational constraints in MRP calculations, and they do not provide optimal cost solutions for blending juices.

Since most large-scale MRP systems do not consider capacity or material constraints, it is hard to obtain even non-optimal solutions to blending and logistics problems. The Welch's MRP system uses regenerative MRP logic. For even minor changes to bills of material, a complete run of the MRP system becomes necessary to obtain new net requirements for Concord and Niagara. The Welch's MRP system takes about six hours per run. This virtually eliminates the ability to interactively find non-optimal solutions using the Welch's MRP system.

Welch's lacked a formal system to optimize raw material movement and recipes used for production. The operations management literature shows several solutions for this problem (see Matta and Miller, 1993; Liberatore and Miller, 1985; and Markland and Newett, 1976). Several of these solutions build on the models of hierarchical integration set forth by Hax and Meal (1975). The work of these authors becomes critical to planning in the process industries because of their treatment of capacity. Taylor, Seward, and Bolander (1981) note that process industries tend to schedule capacity first, then materials. The existing cost accounting and MRP systems at Welch's lacked the ability to consider capacity such as rates of concentration and capability of transporting grape juice between plants. Within the context of capacity, Welch's systems needed consideration of a wide set of feasible recipes taking into account timing of new crop juice availability.

The approach we took to improve the cost accounting and MRP systems involved developing a third model that works independently, but draws data from the cost accounting system. Both the cost accounting and MRP systems calculated requirements for grape juice correctly, but each lacked the ability to calculate optimal cost recipes and interplant transfer schedules based on operational constraints experienced by each plant. Without consideration of operational constraints, the output from the cost accounting and MRP systems provided little practical use in making decisions on how best to use the grape crop.

By employing a third model we envisioned a recursive solution method where the existing cost accounting system initially acts as a database, providing information on grape juice demand to a third model. In turn, the third model calculates optimal recipes and interplant transfer schedules based on operational constraints and cost. Upon completion of this calculation, optimal recipes serve as feedback, and are input into both the cost accounting and MRP systems. The next output of both these systems will then reflect an optimal cost plan and set of recipes that meets operational constraints.

We formulated the third model as a linear program and used a spreadsheet optimizer (What's Best) to find a solution. Spreadsheets provided a natural interface for end users to see the benefits of management science and model building (see Leon, Przansnyski, and Seal, 1996; Winston, 1996; and Plane, 1994).

We began operation of the third model in the spring of 1994. During the first year of operation, the third model saved Welch's between $130,000 and $170,000 in reduced inventory carrying cost. For a more detailed description of this example please refer to Schuster and Allen (1997a).

CMRP AND A CRITICAL RESOURCE

Every CG firm has a critical piece of processing equipment that requires intensive scheduling. At Welch's, we have a large, complex piece of equipment called a concentrator. The purpose of a concentrator is to evaporate water from single-strength juice under a vacuum, producing a concentrated form of juice. Welch's sells the concentrate in retail stores and to industrial customers. Packaging lines consume the concentrate as part of finished goods production. In this sense, concentrate becomes classified as dependent demand. The Welch's MRP system schedules concentrate production assuming infinite capacity, and with no regard to an optimal cost solution. Often, a concentrator produces several types of concentrate, causing difficulty in sequencing.

The scheduling of the concentrator becomes a single-level, lot sizing problem under conditions of limited capacity. In the following example, we apply the heuristic documented in Allen, Martin, and Schuster (1997) to solve the finite loading of the concentrator.

Table 1 shows costs and setup times for production of five types of concentrate. Capacity absorbed refers to the hours of concentrator time needed to make 1,000 gallons of concentrate. Estimated setup cost, holding costs, and setup time, along with forecast demand per week (see **Table 2**), round out the initial data required to run the heuristic. The forecast demand comes directly from the Welch's MRP system and represents lot-for-lot

Table 1. Inputs to the scheduling heuristic.

Item	CAPACITY ABSORBED (hrs/1000 gal)	HOLDING COST ($/1000 gal)	SETUP COST ($/setup)	SETUP TIME (hrs)
A	2.0	$10	$200	1.0
B	2.0	$10	$220	1.0
C	1.5	$10	$150	1.0
D	1.5	$10	$300	2.0
E	4.0	$10	$2,000	4.0

Table 2. Demand forecast—gallons of concentrate required per time period.

	Time Period									
Item	1	2	3	4	5	6	7	8	9	10
A	3.0	7.6	18.9	24.2	17.6	4.4	6.2	8.4	12.6	13.4
B	4.4	1.1	4.0	5.5	4.1	4.3	4.3	4.4	1.1	4.0
C	0.0	0.0	0.0	0.0	2.3	0.9	1.9	1.1	0.0	0.3
D	0.7	0.8	1.6	0.8	0.8	0.0	0.0	0.0	0.8	0.8
E	0.0	0.0	0.0	0.2	0.1	0.2	0.2	0.2	0.9	2.9

requirements. The forecast demand exhibits the lumpy nature often associated with dependent demand.

Capacity available for concentrator production varies from week to week. **Table 3** shows the capacity limits we imposed on the concentrator. Notice that capacity starts out at 60 hours per week, then decreases to 40 hours per week, and finally, the concentrator totally shuts down in week 6. This represents a particularly nasty pattern of available capacity to schedule using finite planning methods. This is a very hard problem to do by hand.

Table 3 shows the results of the scheduling heuristic. In **Table 4** we show the projected ending inventory for each period based on the production plan. All production fits within capacity constraints, and the total cost of the 10-week production plan equals $10,944. The heuristic calculated this solution in several seconds.

We plan to use the heuristic as part of the MRP system at Welch's. By downloading lot-for-lot requirements from the MRP system into a spreadsheet, we can run the heuristic using visual basic. The quick solution times of the heuristic make CMRP a snap.

Table 3. Planned production per time period in gallons.

Item	Time Period 1	2	3	4	5	6	7	8	9	10
A	10.1	29.5	19.5	0.0	16.6	0.0	6.2	21.0	0.0	13.4
B	9.5	0.0	0.0	13.9	0.0	0.0	9.8	0.0	0.0	4.0
C	0.0	0.0	0.0	0.0	3.2	0.0	3.0	0.0	0.0	0.3
D	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.8
E	0.0	0.0	0.0	0.5	0.0	0.0	1.3	0.0	0.0	2.9
PRODUCTION CAPACITY	60	60	40	40	40	0	60	60	0	60
REMAINING CAPACITY	9.7	0.0	0.0	5.2	0.0	0.0	11.3	13.8	0.0	2.9
ADDITIONAL CAP. REQUIRED	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4. Ending inventory per time period in gallons.

Item	Time Period 1	2	3	4	5	6	7	8	9	10
A	7.1	29.0	29.6	5.4	4.4	0.0	0.0	12.6	0.0	0.0
B	5.1	4.0	0.0	8.4	4.3	0.0	5.5	1.1	0.0	0.0
C	0.0	0.0	0.0	0.0	0.9	0.0	1.1	0.0	0.0	0.0
D	4.0	3.2	1.6	0.8	0.0	0.0	0.0	0.8	0.0	0.0
E	0.0	0.0	0.0	0.3	0.2	0.0	1.1	0.9	0.0	0.0

CONCLUSION

Widespread, applied CMRP in the process industries represents a realistic goal achievable in the next five years. In the near term, process-oriented firms can use several methods to turn traditional, infinite-capacity MRP systems into CMRP. The level of competition in the marketplace, combined with the increasing trend toward supply chain integration, will force CMRP as a necessity to many in the process industries.

In the long term, CMRP may define the next generation of material planning systems. However, it's hard to envision large-scale CMRP without use of mathematical programming and heuristics. The trend will push APICS toward model-based solutions and increased emphasis on applied mathematics in decision making. The future skills of APICS practitioners will need to meet the challenge of a job world filled with mathematics.

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