Capacitated Materials Requirements Planning and its Application in the Process Industries

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ABSTRACT

Although material requirement planning (MRP) procedures have long been an accepted practice, these systems suffer from shortcomings that limit their usefulness for firms in the process industries. This paper describes a two-level, spreadsheet-based procedure developed at *Welch's*, the largest processor of Concord and Niagara grapes, to perform integrated capacity planning. In addition to contending with capacity limitations, *Welch's*, like many companies in the process industries, must consider the logistics of inter-plant transfers, special processing requirements, as well as proprietary product recipes when designing an MRP system.

Key words: Material Requirements Planning, Supply Chain Management, Integrated Capacity Planning

INTRODUCTION

Materials requirements planning (MRP) is an old area of study within business. Alfred Sloan writes of MRP type calculations as early as 1921 in his book My Years With General Motors.[1] Modern MRP plays an important role in reducing inventory and improving the manufacture of complex industrial products. In spite of its success, most MRP applications lack proper attention to capacity. As Billington, *et al.*[2] state, "MRP systems in their basic form assume that there are no capacity constraints. That is, they perform 'infinite loading' in that any amount of production is presumed possible…"

The lack of capacity limits in MRP systems is at odds with firms in the process industries. Process-oriented firms have manufacturing operations that involve mixing, separating, forming, and chemical reactions (including such industries as food, chemical, pharmaceutical, plastics, paper, and biotechnology).[3] The process industries are logistics intensive, and multi-plant operations are common. Flows of raw materials and finished goods within the supply chain can undergo disruption when capacity constraints place limits on logistical and production systems. A number of process-oriented firms report problems with traditional MRP and seek alternatives[4]. Through a case study of *Welch's* we explore the attributes of the process industries that permit capacitated material requirements planning (CMRP) in practice.

COMPANY HISTORY

Welch's,Inc. is the worlds largest processor of Concord and Niagara grapes with annual sales surpassing $600 million per year. Founded in 1869 by Dr. Thomas B. Welch, the company now produces a variety of fruit products for distribution in domestic and international markets. *Welch's* is the production, distribution, and marketing arm of the National Grape Co-operative Association (NGCA) headquartered in Westfield, New York. The membership of the NGCA includes 1,450 growers who cultivate 46,000 acres of vineyards clustered in the northern parts of the United States. The members of the NGCA produce Concord and Niagara varieties of grapes. The Concord grape variety is purple in color and it is grown in the cooler regions of the United States. The Niagara grape variety is light in color and also is grown in cooler climates. Major growing areas for Concord and Niagara grape varieties include western New York, northern Ohio, and northern Pennsylvania (all three near Lake Erie), western Michigan, and south-central Washington.

Welch's operates raw grape processing plants near the growing areas of NGCA members. During harvest, the plants process raw grapes into juice. Each plant also produces bottled juices, jellies, jams, and frozen concentrates for retail sale. The plants represent a pure form of vertical integration in agribusiness since they handle all the steps from pressing grapes into juice to distributing finished products. In total, each year the plants process nearly 300,000 tons of grapes into more than 200 finished products. In accomplishing this task, planners must contend with uncertain demand requirements, finite production capacity, and limited storage space. Ineffective planning can lead to increases in costs, wasted raw materials and poor levels of customer service.

TRAITS OF PROCESS MANUFACTURING THAT SUPPORT CMRP

When studying the process industries, researchers encounter a wide range of manufacturing environments. 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 manufacturing and logistics planning systems that cut across all process industry segments.

In this study, we focus our attention on the consumer products (*CP*) segment of the process industries in which *Welch's* competes. This segment represents a large part of the U.S. economy and highlights some interesting problems in planning and control. Effective solutions for the *CP* segment also find application in other segments of the process industries.

Intense competition and high expectations for customer service dominate the business environment of *CP* firms. Demand varies with time as promotional activity often causes wide swings in week to week shipments of finished products. Unexpected events sometimes trigger surges in demand. For example, in 1997 a research study reported the benefits of purple grape juice in the prevention of heart disease.[5] This caused a huge increase in demand for *Welch's* grape juice. The sudden increase in demand placed pressure on *Welch's* planning and logistics systems to respond with continued high levels of customer service. In spite of sudden changes in demand, it is always important for *CP* firms to maintain an uninterrupted stream of products to the market place. Any sort of disruption can lead to loss of sales and decreased market share.

To deal with dynamic demand for end items, *CP* manufacturers must account for capacity constraints at all levels of the supply chain. This ambitious goal remains elusive for most *CP* firms.

MRP is an important planning system situated deep in the supply chain structure. For most process-oriented firms, the master production schedule (MPS) represents the lot size and timing of end-item production to meet customer demand. Some process-oriented firms also master schedule intermediate materials and co-products/by-products if these are important to plant operations.

The MRP system at *Welch's*, in turn, calculates the net requirements from the MPS for raw materials and work-in-process (WIP). Since 1984, *Welch's* has employed several methods to calculate the MPS. Early efforts dealt with a deterministic simulation to find an infinite capacity MPS.[6] Later efforts include development and application of finite capacity planning models and hierarichal integration.[7]

From experience we find that raw material processing equipment sometimes becomes the capacity bottleneck that limits WIP production. This can force unwelcome changes to the MPS. These changes often result in sub-optimal solutions that elevate cost and reduce customer service though out the supply chain.

The application of CMRP at *Welch's* plays an important role by reducing the chance of disruptions to the MPS caused by shortages of WIP. Within the supply chain, proper execution of the MPS helps to insure adequate inventory levels and high levels of customer service. Effective scheduling of important process equipment through CMRP also leads to greater capacity utilization.

Given the importance of CMRP in *CP* manufacturing, the literature on supply chain management offers few records of its application in dynamic systems. As well, there are few references on the complex interactions of planning and control systems, and the recursive nature of planning in practice.

In a review of published research, we find early writing on the supply chain involves *static* depiction with focus on design, analysis, and strategy. Beyond the pioneering work of Porter,[8] other authors such as Shapiro, *et al.*[9] describe the "value chain" for a *CP* company as a single mathematical model with an optimal solution. Lee and Billington,[10] and Arntzen, *et al.*[11] further develop *aggregate planning* approaches by modeling inventory and production in the large-scale supply chains of two major computer companies. Taube-Netto[12] provides an interesting supply chain model for agricultural production in Brazil while Erkut[13] discusses a distribution model for household products in Turkey. Erkut's work hints at some of the dynamics experienced in the distribution portion of the supply chain, but makes no mention of other systems beyond

Distribution Requirements Planning (DRP). Finally, Camm, *et al.*,[14] write a fascinating study about re-structuring a complex supply chain. The dollar savings are impressive.

All of these papers make a strong case for static or aggregate modeling of the supply chain. However, none makes mention of operational systems, like CMRP, that are important for tactical planning within supply chains. In Kent and Flint's[15] study of the evolution of logistics thought, they speculate the future holds more emphasis on integration where firms look at "logistics processes as extended across total supply chains." We believe the practice of linking the various planning systems spanning an entire supply chain requires some form of hierarchical integration based in mathematical modeling. Hax and Meal[16] provide the first treatment of hierarichal production planning (HPP) using linear programming to do product family planning and disaggregation. Their ideas are expanded by Bitran, *et al.*[17] who provide a comparison between HPP and MRP. Liberatore and Miller[18] apply HPP in process manufacturing with de Matta and Miller[19] giving a follow-up report of the system evolution over an eight year time period.

These types of models serve as effective agents to mitigate the devastating effects of wide demand swings on supply chain costs and customer service. Sterman[20] offers good reason to employ rational models as an alternative to human decision making in dynamic systems. To accomplish CMRP at *Welch's* we choose to use several models arranged in an hierarchy that interact with existing cost accounting and MRP systems. Vashi, *et al.*[21] captures the spirt of combining several models and we adopt this mode of thinking in our system design of CMRP. However, moving from the theory to actual *implementation* of CMRP at *Welch's,* and for *CP* manufacturing in general, raises three practical issues:

- Multi-level Vs Single-Level - For process-oriented firms that have deep bills of material, CMRP must optimize cost while meeting capacity constraints across **all** levels of the bill of material. This offers a difficult problem with few, if any, practical solutions. Optimization of cost while meeting capacity constraints is more tractable when dealing with a single level of the bill of material. However, this could lead to local optimal solutions in cases where a deep bill of material exists.

- WIP Lot-sizing Vs Raw Material Lot-sizing - WIP and raw materials often require **different** lot-sizing methods to deal with the conflicting priorities of internal versus external customers. Practitioners commonly use the same lot-sizing method for WIP and raw materials. This may lead to inappropriate lot-sizing solutions.

- Multi-Plant Vs Single Plant - Many process-oriented firms have **networks** of manufacturing plants that depend on each other for raw materials. This increases the complexity of CMRP, raising the need for additional computer models to plan transfers of critical raw materials between plants based on capacity constraints.

These three critical issues raise serious questions concerning the viability of CMRP in practice. A survey from the early 1990's shows practitioners rank capacity management a very high business priority.[22] Yet, another survey from the same time indicates practitioners most commonly use the simplest MRP lot-sizing techniques.[23] This in spite of research showing that less sophisticated lot-sizing techniques are poor cost performers in multi-level systems.[24] In all three of these studies the authors only consider traditional MRP systems.

With the lack of interest in lot-sizing techniques by practitioners, why should we suppose CMRP is a viable planning method for the process industries? There are two answers to this question.

First, existing survey results do not make mention of the proportion of process-oriented firms compared to the number of total replies. Few of the software companies participating in the survey appear to have roots in the process industries. For this reason, results favor the current condition of MRP in discrete manufacturing rather than a fair appraisal of its application in the process industries. Taylor and Bolander[25] 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 MRP in discrete manufacturing do not apply to the process industries. Common observation shows that lot-sizing with capacity constraints takes on great importance. 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 of its intended application. Most process-oriented firms understand the value of an integrated supply chain, spanning from the customer back to the vendors who provide the basic raw materials. In such a system, recognition of finite capacity at each link of the supply chain becomes important. MRP must include capacity constraints to promote a smooth flow of WIP in support of the MPS and transfers of raw materials between plants.

Given some time for reflective thought, process-oriented firms can mold selective aspects of CMRP into a practical tool for planning. This requires an honest analysis of the business environment, along with a desire to overcome the three implementation issues, described earlier, that limit the use of CMRP among practitioners.

THE IMPLEMENTATION OF CMRP AT *WELCH'S*

One trait of *CP* manufacturing sets it apart from all other types of firms. Most *CP* firms produce simple products in large quantities. Often the products have flat bills-of-material structures. The flat structure allows *Welch's*, and other *CP* firms, a greater chance of surmounting the three critical issues of CMRP implementation:

- With flat bill of material structures, *CP* firms can apply **single level** CMRP with less risk of finding a solution far from the global optimum for cost.

- Because of flat bills of material, *CP* firms have fewer levels that require critical lot-sizing decisions. Lot-sizing procedures can be **tailored** for specific situations, rather than using a single lot-sizing method for all products and levels in the bill-of-materials.

- Finally, flat bills of material help simplify the coordination of material flows in multi-plant situations. This allows for **specialized solutions** like CMRP.

In conjunction with flat bills-of-materials, product families in *CP* manufacturing often take on the additional trait of a "V" structure. Umble[26] notes that plants producing V-shaped product families have the following common characteristics:

1. The number of end items is large compared to the number of raw materials.
2. All end items sold by the plant are processed in essentially the same way.
3. The equipment is generally capital intensive and highly specialized.

These attributes are typical of plant operations at *Welch's*. All fruit juice processed in *Welch's* plants advances through similar processing steps involving specialized equipment. This type of process organization raises the prospect of bottlenecks forming where lack of capacity exists, restricting flow through the supply chain.

We also notice that the unique V-shaped product family structure has a large impact on the planning of WIP lot-sizes at *Welch's*. Hence, the shape of product family structure influences our thinking in MRP system design.

Finch and Cox[27] observe that V-shaped product families influence the size of buffers required to keep bottleneck work centers at full capacity. They state the need for constraint-based planning systems where V-shaped product families exist. The historical tendency of *CP* firms to install traditional MRP systems directly conflicts with the need to sequence production based on capacity constraints. In situations of insufficient capacity at critical work centers, the supply chain experiences interruption in flow and customer service suffers. CMRP plans production with capacity constraints assumed, avoiding the interruptions in flow that ultimately cause poor customer service.

A final motivation for applying CMRP at *Welch's* involves the company's unique business organization. With the agricultural cooperative structure, *Welch's* has a great opportunity to achieve competitive advantage through vertical integration of the supply chain. However, this same integration also requires large investments in fixed assets such as processing and transportation equipment. Because of the scale of capital investment in the process industries, asset utilization becomes an important strategic goal. To insure proper use of assets within the supply chain, *Welch's* began a review of how it uses MRP to coordinate plant operations. Lot-sizing is at the heart of MRP and is a good starting point for the analysis of asset utilization.

Different lot-sizing approaches tend to follow a similar path of logic. All approaches attempt to calculate the trade-off between set-up cost and inventory carrying cost. Some lot-sizing methods perform cost trade-off's explicitly through very complex calculations. Other methods use simple assumptions to determine the "best" lot-sizes. Early work on lot-sizing during the 1950's sought to obtain optimal solutions while ignoring capacity limitations. Wagner and Whitin[28] led the way in this area publishing innovative research on optimal lot-sizing techniques based on cost, dynamic demand, and infinite capacity. Since the early 1980's, researchers have made substantial improvements on earlier work by developing some practical methods of lot-sizing while considering capacity constraints. These developments along with advances in desktop computing make CMRP a realistic posibility for application within the supply chain of *CP* firms. At *Welch's*, the combination of flat bills-of-material structure, V-shaped product families and vertical integration further reinforces the opportunity to apply CMRP.

We now turn our attention to a review of the literature of CMRP. This discussion offers a backdrop to the use of CMRP at *Welch's*.

COMMENTARY ON THE LITERATURE OF CMRP

The operations management literature contains much discussion about MRP. Drawing from the literature, we feel CMRP solutions fall into two broad categories: mathematical programming-based solutions, and heuristic-based solutions.

CMRP and Mathematical Programming

Nahmias[29] defines mathematical programming as "a set of equations that expresses the most important relationships of a real system. One seeks the values of the decision variables that will be optimal according to the system of equations." Mathematical programming uses a number of different formulation and solution techniques. As a modeling tool, it is very flexible and the literature shows a number of applications.

Early efforts to address lot-sizing with limited capacity trace to a mathematical formulation by Dzielinski and Gomory.[30] Their approach uses large scale linear programming (LP) with "sifting" decision variables that choose the best lot size while still meeting capacity constraints. The method applies to either WIP or end item lot-sizing. In practice, the "sifter" requires specialized knowledge of LP. It is unclear if the mathematical formulation actually produces relaxed binary integer solutions for all types of lot-sizing problems. The authors did not offer theorems to support their claims. We could find no documentation of its use by any firm in the process industries. However, the "sifter" does provide an idea of the complexity involved in finding optimal solutions to capacitated lot-sizing problems. We have solved small versions of the Dzielinski-Gomory formulation using binary integer programming. The model serves as an effective instructional tool for finite planning.

The work of Dzielinski and Gomory deals with single-level, lot-sizing and can yield a local optimum even in situations where there are few levels to the bill of material. Other authors attempt to find multi-level, optimal solutions. McLaren[31] provides an early example. This work uses binary integer programming but also assumes infinite capacity. For large problems, it becomes difficult to find solutions using binary integer programming. Again, as with the sifter, it is hard to put McLaren's formulation into practice. To our knowledge, there are no applications in the process industries.

Billington, *et al.*[32] offer a comprehensive look at CMRP but limit their writing to theoretical exploration of solution methods using mixed integer programming. Meanwhile, Tempelmeier and Derstroff[33] take an equally rigorous approach to solving multi-level planning problems by means of Lagrangean relaxation and decomposition to find a lower bound solution. They find upper bounds through a heuristic finite loading procedure. Both of these papers use intricate mathematics to find optimal lot-sizing solutions. To date, these methods are outside the knowledge base of most practitioners. However, this research work does point the direction toward innovative applications of integer programming to attain CMRP.

Some authors write of successful mathematical programming applications to multi-level, capacitated lot-sizing problems. Most notable is the work of Leachman, *et al*.[34] They report on the application of LP at Harris Corporation - Semiconductor Sector as a replacement for the previous, infinite capacity, MRP system. To solve the large-scale LP problem, they use a decomposition strategy, breaking the formulation into sub-problems that are much easier to solve. This extensive project took several years to complete, but provided solid results in raising on-time deliveries from 75 to 95 percent without increasing inventory.

Mathematical programming offers great potential for solving CMRP problems. Broader application of this method depends on increasing computer power and the ability to solve large-scale mixed integer mathematical programming models quickly. The level of specialized knowledge to operate these systems may limit their overall use in the process industries for the immediate future.

CMRP and Heuristics

Where mathematical programming promises 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 take a long time to, or never, reach the one best, optimal solution. On the other hand, heuristics can 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 in advance the performance of heuristics other than through intensive testing.

Commercial software companies selling finite planning systems seldom offer test data on performance. However, several researchers report on testing that compares heuristic solutions to optimal solutions obtained through mathematical programming. After testing the performance of various lot-sizing heuristics to the Common Cycle Scheduling Problem (CCSP) El-Najdawi[35] states, "…we have shown that settling for a satisfactory or sub-optimal solution to the lot-sizing scheduling problem is sufficient." He concludes, "…we have provided enough evidence from the literature that the cost and time spent to find an optimal solution to the lot-size scheduling problem is high and could not be easily justified." Trigiero, *et al.*[36] also show the "solution gap" between optimal solutions and their LP/heuristic solutions is small for capacitated scheduling problems with set-up times. Both of these researchers give strong evidence for using heuristics to achieve quick solutions to CMRP problems.

Dixon and Silver[37] provide early work on a heuristic for single level, lot-sizing with capacity constraints. Their work links to the infinite capacity lot-sizing method by Silver and Meal.[38] The Silver-Meal heuristic performs well under a number of different conditions and is simple to use.

Allen, *et al.*[39] improve upon the Dixon-Silver heuristic by adding set-up time and by using an Excel[40] spreadsheet combined with visual basic programs to calculate capacitated lot-sizes for end items. They test the heuristic performance over a wide range of real conditions and list test results as part of their research. Their approach also applies to WIP lot-sizing situations. Recent research work by D'Itri, *et al.*[41] further improves upon the Dixon-Silver heuristic by adding a second model that does sequence-dependent scheduling of lot-sizes. The model formulates lot sequencing as a traveling salesman problem and uses the nearest neighbor variable origin - heuristic (NNVO) as a solution method.[42]

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 show consistent performance under all patterns of demand. The practitioner should apply heuristics in those cases where previous testing provides confidence of success.

We now continue our discussion by describing the two-level planning system for CMRP at *Welch's*. Broadly speaking, it embodies the principles of hierarchical integration, but it also has significant interaction with existing cost accounting and MRP systems. This interaction makes CMRP at Welch's unique. The first level deals with multi-plant, aggregate planning involving capacity and material constraints. For this model, we use an LP to find a solution. The second level of the planning system at *Welch's* is a CMRP model for a critical piece of machinery that processes raw grape juice. This example highlights the use of a heuristic to find a solution.

THE GRAPE HARVEST AND JUICE PLANNING AT *WELCH'S*

In the fall, fruit growers deliver grapes to *Welch's* for pressing into juice. *Welch's* stores the grape juice in large refrigerated tanks for year round use in production. Supply and demand for grape juice is seldom equal. To balance supply and demand between major growing areas, *Welch's* must make decisions on the best use of the grape crop. Typical decisions include:

1. How much concentrate to transfer between plants,
2. The mode of transportation (rail or truck) for transfers of concentrate,
3. Recipes to use for major product groups.

Welch's has a refined cost accounting system that calculates requirements for grape juice by month. The system accounts for the recovery loss and the cost of converting grapes into finished product. In June of 1996, the company implemented an integrated MRP system that calculates time-phased requirements for all components needed to manufacture finished products. The new MRP system takes advantage of relational data base information technology and operates on a mini-computer. Both the cost accounting and MRP systems allow for extraction of data to computer spreadsheets though data warehousing technology. Although state-of-the-art, these systems still suffer from two major limitations: a) they ignore operational constraints in MRP calculations and b) they do not provide optimal cost solutions for blending juices.

With most large-scale, commercial MRP systems it is hard to find a feasible solution to blending and logistics problems that contain many variables. The *Welch's* MRP system uses regenerative MRP logic. For even minor changes to bills of material, a complete run of the MRP system (taking about six hours) becomes necessary to obtain new net requirements for grape juice. This shortcoming virtually eliminates the possibility of finding feasible solutions by trial and error.

Our approach to improve the cost accounting and MRP systems involves developing a *third model* that works independently, but draws data from the cost accounting system.[43] Because the *third model* deals with corporate wide logistical decisions, we call it the juice logistics model (JLM).

By applying the JLM we envisioned a recursive solution method where the existing cost accounting system initially acts as a data base, providing information on grape juice demand to the JLM (see figure 1). In turn, the JLM 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 of these systems will then reflect an optimal plan.

Please place figure 1 about here

The work of Geoffrion[44] supports our notion of the JLM. He writes about using "auxiliary models" to give solutions in closed form for insight into large mathematical programming models. In a similar line of reasoning, we use the JLM as a quick "scratch pad" for optimizing the recipes and flow of grape juice within the supply chain network. This approach greatly improves our decision making process for grape juice management in each facility as well as coordinating the transfer of juice between plants.

In 1993, we began to formulate the JLM as an LP and used a spreadsheet optimizer (What's Best)[45] to find a solution. The mathematical formulation of the JLM is straightforward (interested readers can find a summary of the JLM in the Appendix). We choose a spreadsheet approach for the JLM because it provides a natural interface for end users to see the benefits of management science and model building.[46] The application of spreadsheet optimization is gaining acceptance as more business schools teach it as part of modeling courses. Jones[47] feels the powerful visualization properties of spreadsheets may one day supplant traditional algebraic modeling languages currently in use for mathematical programming. By using the multi-dimensional indexing capabilities and the point and click features of Excel, we were able to code the JLM formulation (1,320 decision variables and 1,395 constraints) in less than six hours. Typical solve times are about one minute on a P-200 microcomputer.

We began operation of the JLM in the spring of 1994. During the first year, *Welch's* saved between $130,000 and $170,000 in reduced inventory-carrying cost. In recent years, we have used the JLM extensively to plan the proper storage space requirements during successive years of large grape crops.

The JLM has become invaluable in allowing us to simulate the effect of different recipes on year-to-year carryover of Concord juice.

The JLM is an effective aggregate-planning model for coordinating supply chain operations. However, to support the complex logistics of juice movements within Welch's supply chain we needed an additional, more precise modeling tool for scheduling of processing equipment. In the next section we take a heuristic previously designed for finished goods scheduling and apply it for CMRP. The scheduling heuristic is the second level of the planning system at *Welch's* and our final topic of discussion.

CMRP AND A CRITICAL RESOURCE

Many *CP* firms have a critical piece of processing equipment, usually large, expensive, and complex that requires intensive scheduling. At *Welch's*, this is a concentrator, which evaporates water from grape juice held under a vacuum, producing a concentrated form of grape juice. The company sells the grape concentrate in retail stores and to industrial customers. *Welch's* also transfers large quantities of grape concentrate between plants to balance supply and demand. Shipping concentrate rather than grape juice greatly reduces transportation cost.

Figure 2 shows the processing steps required to obtain the raw juice for making concentrate. *Welch's* pasteurizes fresh juice from the harvest and stores it in refrigerated tank farms. Time must pass before the grape juice is ready for conversion into concentrate. Raw grape juice contains insolubles that slowly settle to the bottom of the tank. After this settling process, the juice is ready for concentrating.

Please Place Figure 2 here

The *Welch's* MRP system schedules production of concentrate assuming infinite capacity, and with no regard for an optimal cost solution. Often a need exists to produce several types of concentrate, causing difficulty in sequencing. A plant might produce between five and twelve types of concentrates in support of different manufactured products, interplant transfers and sales of grape concentrate to industrial customers. All of these are critical activities within the supply chain of Welch's.

The scheduling of the concentrator is a single-level, lot-sizing problem under conditions of limited capacity. In 1998, we began operating a system to attain CMRP using computer spreadsheets and data from our existing MRP system. The JLM (first level of the planning system) determines the best recipes for major product groups based on aggregate capacity and supply constraints. The MRP system then uses these recipes to calculate requirements for grape concentrate. We in turn use the requirements from the MRP system as input to our CMRP system that schedules the sequence of grape concentrate production based on available capacity of the concentrator.

In the following example, we apply the heuristic documented in Allen, *et al*.[48] to plan the production of several types of concentrate under conditions of limited capacity. Copies of the data and solution method are available for research purposes through the first author by emailing a request to *eschuster@welchs.com*. The heuristic uses the proven Silver-Meal[49] method to determine initial lot-sizes and an economical lot transferring procedure to find the cheapest production plan within available capacity. We use a heuristic instead of an "exact" mixed integer programming model because it gives a quick solution that we have shown is close to optimal.[50]

Table 1 shows costs and set-up times for production of five types of concentrate. Capacity absorbed refers to the hours of concentrator time to make 1,000 gallons of concentrate. Estimated set-up cost, holding costs, and set-up time, along with forecast demand per week (table 2), round out the initial data required to run the heuristic. The demand forecast comes directly from the existing *Welch's* MRP system and represents lot for lot requirements. Note that the forecast demand exhibits the lumpy nature often associated with MRP lot-sizing.

We add no safety stock to the lot for lot demand forecast for concentrate. All safety stock occurs in the form of end item inventory at the MPS level. We also assume a very low carrying cost. Since *Welch's* owns dedicated tank farms, the variable cost of storing juice is very low. This de-emphasis of carrying cost in lot-sizing decisions is a postulate of modern manufacturing theory. Toelle[51] writes: "one might characterize the synchronous manufacturing literature as viewing the proper batch-sizing trade-off as one between set-up costs versus capacity constraints, rather than between set-up costs versus holding costs." Consistent with this statement, *Welch's* assumes a low inventory carrying cost for concentrate and focuses on the trade-off between set-up time and cost, and capacity.

Please Place Table 1 and 2 here

Concentrator production capacity varies from week to week. Table 3 shows the capacity limits we place 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. The problem is nearly impossible to do by hand.

Table 3 shows the results of the heuristic in the form of a production plan for concentrate. In table 4 we show the projected ending inventory for each period based on planned production. Since there is no safety stock, inventory sometimes goes to zero. All production fits within capacity constraints and the total cost of the ten-week production plan equals $10,944. The heuristic calculates this solution in less than 20 seconds on a P-200 microcomputer.

Please place table 3 and 4 here

Processing planners run the heuristic and obtain a satisfactory production plan for the concentrator. Planners then load the timing and lot size of concentration runs into the MRP system as firm planned schedules. By using this procedure, *Welch's* modifies an existing MRP system into CMRP insuring proper scheduling of the concentrator to support production needs, interplant transfers, and industrial sales. The quick solution times from using the heuristic make CMRP practical for "what-if-analysis." As an example, we are able to see the cost trade-off of not running the concentrator during winter months when utility costs are at a peak. Other applications of CMRP include better balancing of work schedules and improvement of recoveries by optimizing the length of production runs.

CONCLUSION

Widespread, application of 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 MRP systems into CMRP. Through a study of *Welch's* we have demonstrated how the layering of models, and their interaction with existing MRP and cost accounting systems, can achieve CMRP in practice. With increasing levels of competition, along with the trend toward supply chain integration, CMRP will become a necessity at many firms in the process industries.

In the longer term, CMRP will define the next generation of materials planning systems. However, it is hard to envision large scale CMRP without intensive use of mathematical programming, heuristics, and recursive solution methods. This trend will push logistics managers in the process industries toward model based solutions and more emphasis on applied mathematics in decision making. Future skills of logistics managers will need to meet the challenge of a profession that is rapidly increasing its reliance on mathematical models.

APPENDIX: The Juice Logistics Model

i = month, where i=1,2,...I

j = product group, where j=1,2...J

k = plant, where k=1,2,...K

Decision Variables:

TS(i,j,k) = Grape juice shipped to customers in month i, for product group j at plant k (in tons)

TI(i,k,m) = Grape juice transferred into plant k from plant m during month i (in tons)

TO(i,k,m) = Transfers of grape juice out of plant k into plant m during month i (in tons)

EI(i,k) = Ending inventory of grape juice for month i at plant k (in tons)

Costs:

CT(i,k) = Cost of transporting grape juice in month i from plant k (cost per ton)

CR(j,k) = Cost of recipe for product group j at plant k (cost per ton)

CS(12,k) = Carrying cost of storing grape juice in month 12 at plant k (storage cost per ton)

Parameters:

TU(i,j,k) = Total grape juice used (from NGCA plus juice from outside the cooperative) in product j at plant k in month i **(Note - Input comes from the existing MRP System (tons))**
a(i,j,k) = Maximum percentage of grape juice (from NGCA) in product group j for plant k in month i (percentage expressed as a decimal)
b(i,j,k) = Minimum percentage of grape juice (from NGCA) in product group j for plant k in month i (percentage expressed as a decimal)
MI(k) = Minimum ending inventory for plant k at the end of the planning year
OL(i,k) = Limit on outbound shipments for plant k in month i (tons)
SL(k) = Limit on grape juice sold for plant k (tons)
Ivalue(k) = Initial value of grape juice inventory at plant k (tons).
C(i,k) = Crop received in month i at plant k (tons).

Objective Function:

$$Min[\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J} CR(j,k)TS(i,j,k) + \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{m\neq k}^{M} CT(i,m)TI(i,k,m)$$

$$+\sum_{k=1}^{K} CS(12,k)EI(12,k)]$$

Subject to

(1) Beginning inventory

EI(0,k) = Ivalue(k)   For all k

(2) Material balance

$$EI(i,k) = EI(i-1,k) + \sum_{m\neq k}^{M} TI(i,k,m) - \sum_{m\neq k}^{M} TO(i,k,m) + C(i,k) - \sum_{j=1}^{J} TS(i,j,k)$$

For all i,k

(3) Tons sold maximum recipe

$TS(i,j,k) \leq a(i,j,k)TU(i,j,k)$ For all i,j,k

(4) Tons sold minimum recipe

$$TS(i,j,k) \geq b(i,j,k)\,TU(i,j,k) \quad \text{For all i,j,k}$$

(5) Minimum ending inventory

$$EI(12,k) \geq MI(k) \quad \text{For all k}$$

(6) Transfer constraint

$$\sum_{m \neq k}^{M} TO(i,k,m) \leq OL(i,k) \quad \text{For all i,k}$$

(7) Transfer balance

$$TO(i,k,m) = TI(i,m,k) \quad \text{For all i,k,m; } k \neq m$$

(8) Tons sold constraint for each plant

$$\sum_{i=1}^{I} \sum_{j=1}^{J} TS(i,j,k) \leq SL(k) \quad \text{For all plants k}$$

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Item	CAPACITY ABSORBED (hrs/1000 gal)	HOLDING COST ($/1000 gal)	SET-UP COST ($/set-up)	SET-UP TIME (hrs)
Niagara	2.0	$10	$200	1.0
Apple	2.0	$10	$220	1.0
Cranberry	1.5	$10	$150	1.0
White	1.5	$10	$300	2.0
Concord	4.0	$10	$2,000	4.0

Table 1: Inputs to the Scheduling Heuristic

Item	Time Period									
	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10
Niagara	3.0	7.6	18.9	24.2	17.6	4.4	6.2	8.4	12.6	13.4
Apple	4.4	1.1	4.0	5.5	4.1	4.3	4.3	4.4	1.1	4.0
Cranberry	0.0	0.0	0.0	0.0	2.3	0.9	1.9	1.1	0.0	0.3
White	0.7	0.8	1.6	0.8	0.8	0.0	0.0	0.0	0.8	0.8
Concord	0.0	0.0	0.0	0.2	0.1	0.2	0.2	0.2	0.9	2.9

Table 2: Demand Forecast - Gal. of Concentrate Req. per Time Period (1000's of gallons)

Item	Time Period									
	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10
Niagara	10.1	29.5	19.5	0.0	16.6	0.0	6.2	21.0	0.0	13.4
Apple	9.5	0.0	0.0	13.9	0.0	0.0	9.8	0.0	0.0	4.0
Cranberry	0.0	0.0	0.0	0.0	3.2	0.0	3.0	0.0	0.0	0.3
White	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.8
Concord	0.0	0.0	0.0	0.5	0.0	0.0	1.3	0.0	0.0	2.9
PRODUCTION CAPACITY (hrs/wk)	60	60	40	40	40	0	60	60	0	60
REMAINING CAPACITY (hrs/wk)	9.7	0.0	0.0	5.2	0.0	0.0	11.3	13.8	0.0	2.9
CAPACITY SHORTFALL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3: Planned Production per Time Period in Gal.

Item	Time Period									
	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10
Niagara	7.1	29.0	29.6	5.4	4.4	0.0	0.0	12.6	0.0	0.0
Apple	5.1	4.0	0.0	8.4	4.3	0.0	5.5	1.1	0.0	0.0
Cranberry	0.0	0.0	0.0	0.0	0.9	0.0	1.1	0.0	0.0	0.0
White	4.0	3.2	1.6	0.8	0.0	0.0	0.0	0.8	0.0	0.0
Concord	0.0	0.0	0.0	0.3	0.2	0.0	1.1	0.9	0.0	0.0

Table 4 - Ending Inventory per Time Period in Gallons

Figure 1 - Recursive Solution Method

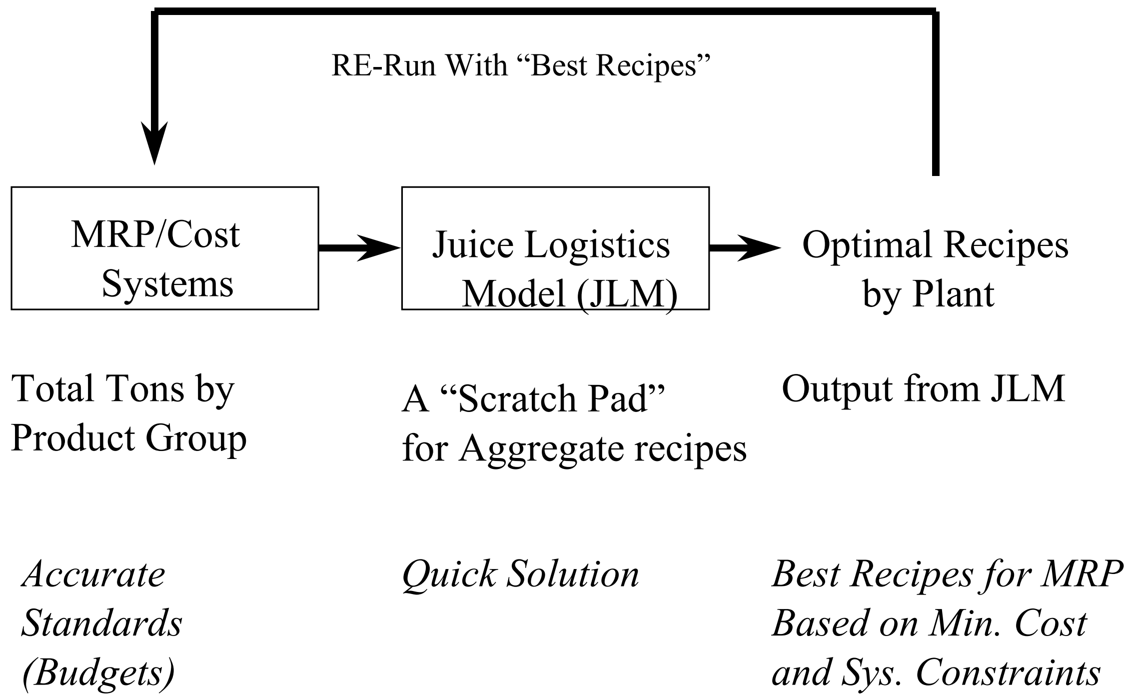

Figure 2 -Steps in Grape Juice Processing