# Learning Objectives

- Define the importance of mathematical modeling in practice
- Understand the theory of capacitated MRP
- Learn how to convert an infinite capacity MRP system into capacitated MRP, using mathematical models (case study)
- Understand how capacitated MRP can optimize cost in the supply chain
- Focus on CPG, with applications in other process industries

# The Process Industries

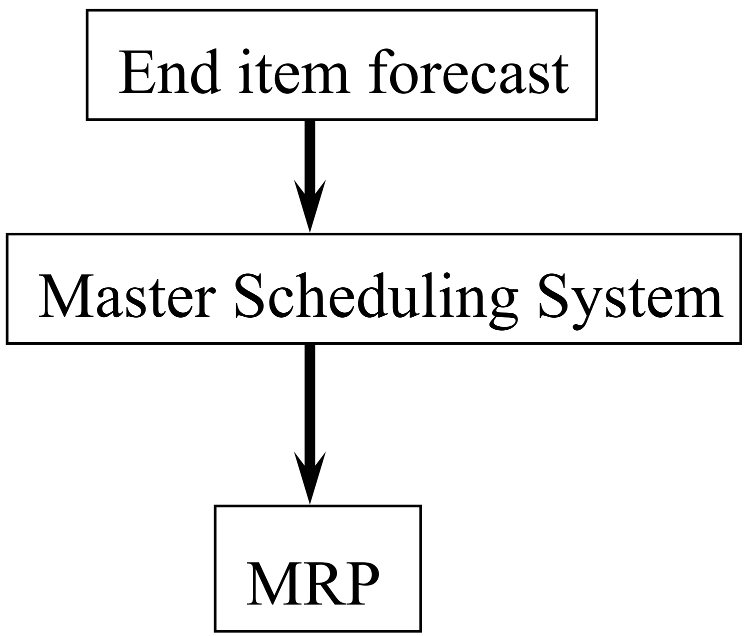
- Have manufacturing operations that include:
  - Mixing
  - Separating
  - Forming
  - Chemical reactions
- Major Industries:
  - Food
  - Chemical
  - Pharmaceutical
  - Paper
  - Biotechnology

# Capacitated MRP (CMRP) Defined:

- **Optimal lot sizing for dependent demand given capacity constraints**
- **Raw materials and work in process**
- **Capacity and cost trade-offs, deep in logistics system**
- **Reduce disruption of the master production schedule (MPS)**

# A Simple Diagram of Planning in Consumer Goods Manufacturing

*Independent Demand*




*Dependent Demand*

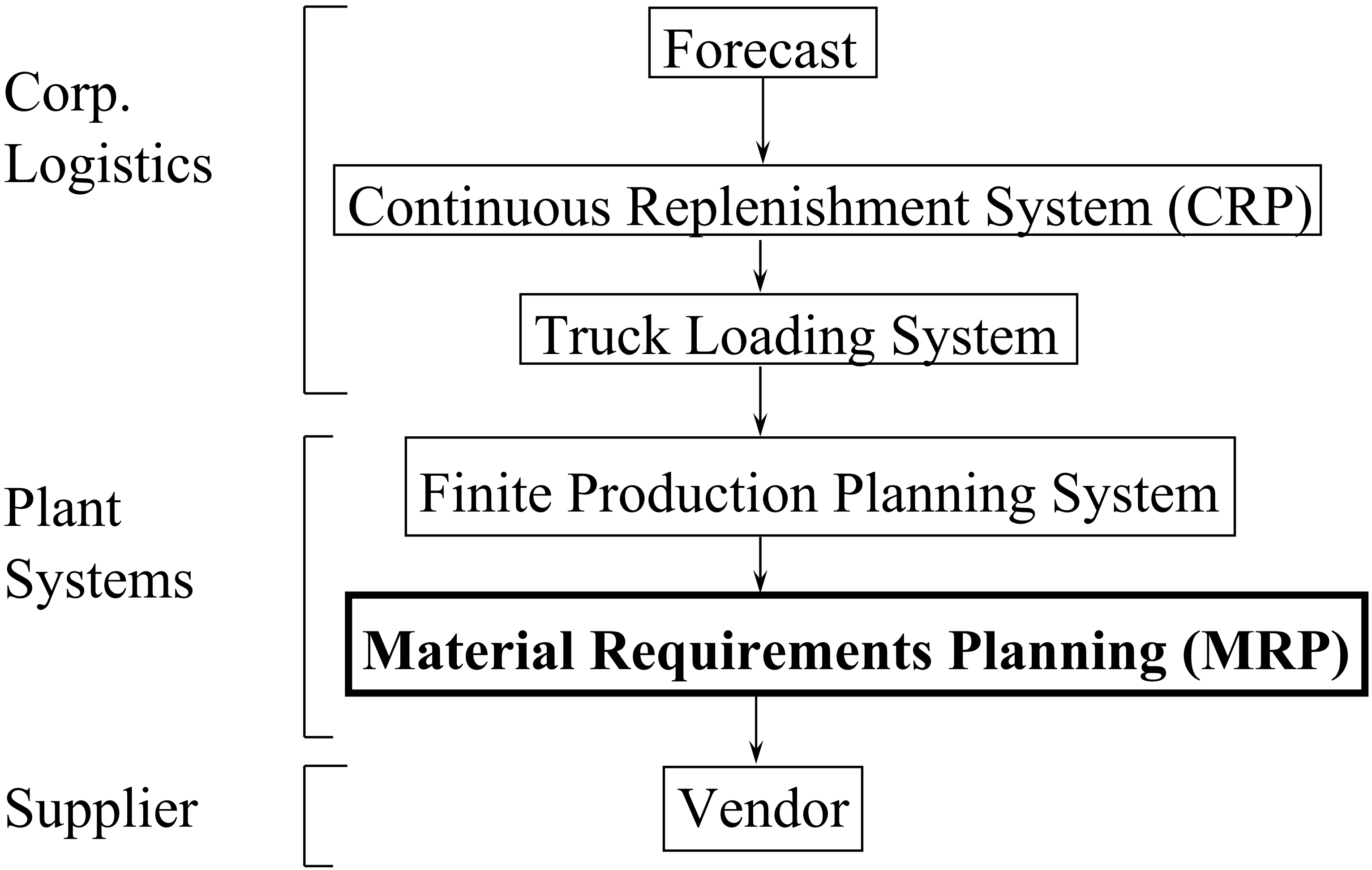
- Finite capacity
- Optimal cost
- Production sequence

- Finite capacity
- Optimal cost
- Raw material and WIP lot sizing

# Why is CMRP Important?

- **Business environment of process-oriented firms is logistics intensive**
- **Infinite capacity logic MRP remains common**
- **Capacity and cost drives all planning and logistical decisions**
- **MRP is part of the integrated supply chain**

# The Supply Chain Model



# Some Examples of Typical CMRP Opportunities in the Process Industries:

- **Problem 1: Planning for raw material flows in a multi-plant manufacturing network**
- **Problem 2: Scheduling a key resource that produces WIP for other manufacturing plants**
- **Both problems represent opportunities to convert an existing infinite capacity MRP system into CMRP using models**

# Remaining Topics:

- **Discussion of <u>problems 1&2</u> in the context of Welch's**
- **Implementation issues concerning CMRP**
- **Potential solution methods to achieve CMRP in practice**
- **The solution Welch's adopted for <u>problems 1 & 2</u>**

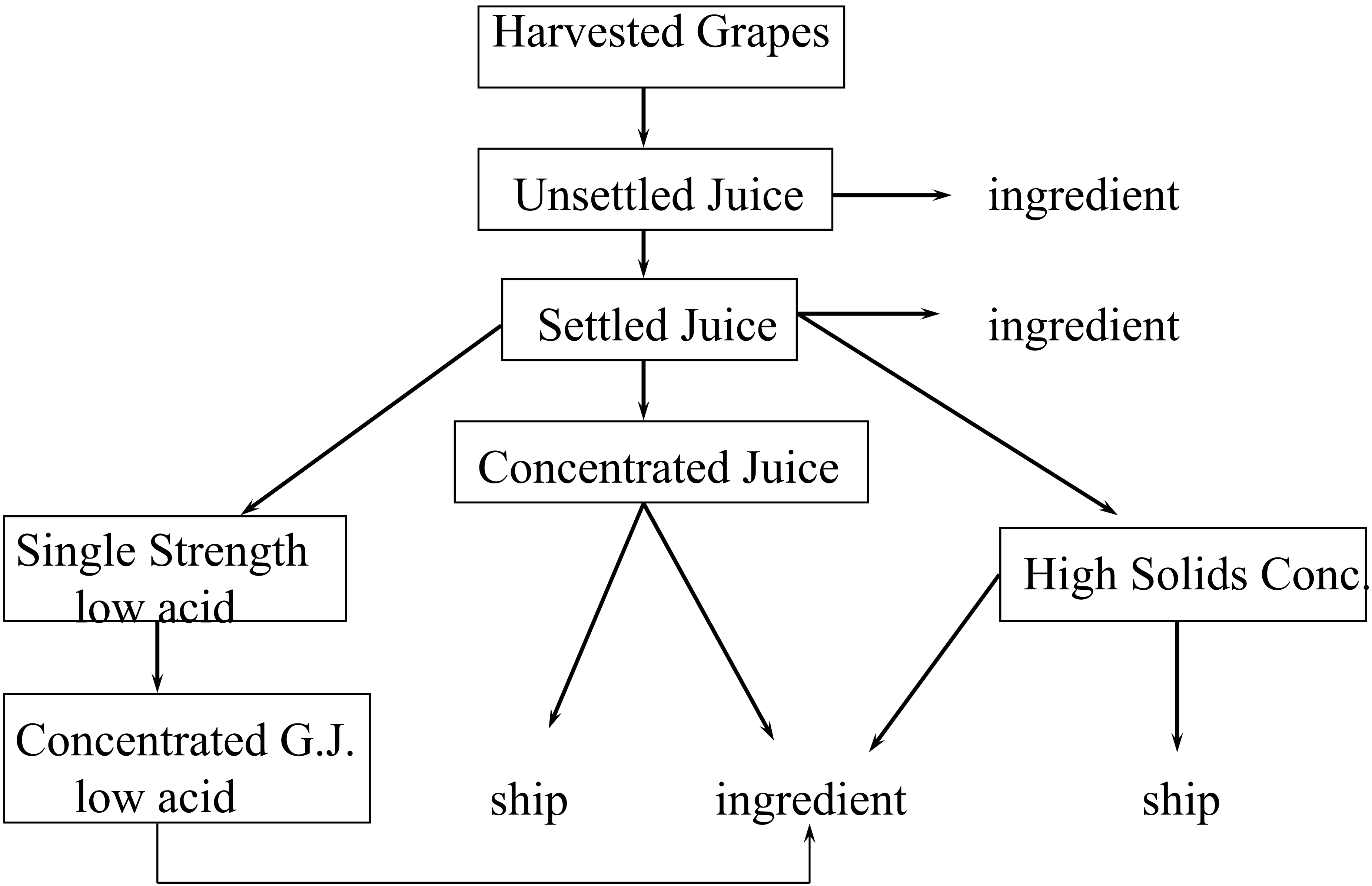
# Welch’s, Inc.

- The world’s largest processor of Concord and Niagara grapes
- Established in 1869 by Thomas B. Welch
- Owned by National Grape Cooperative
- Harvest nearly 300,000 tons of grapes
- Sales surpass $600 million
- Growing areas in NY, PA, MI and WA

# Company Environment

- Dynamic, uncertain demand
- High customer service requirements
- Make-to-stock inventory policy
- Plants located near growing areas
- Full product line at each plant

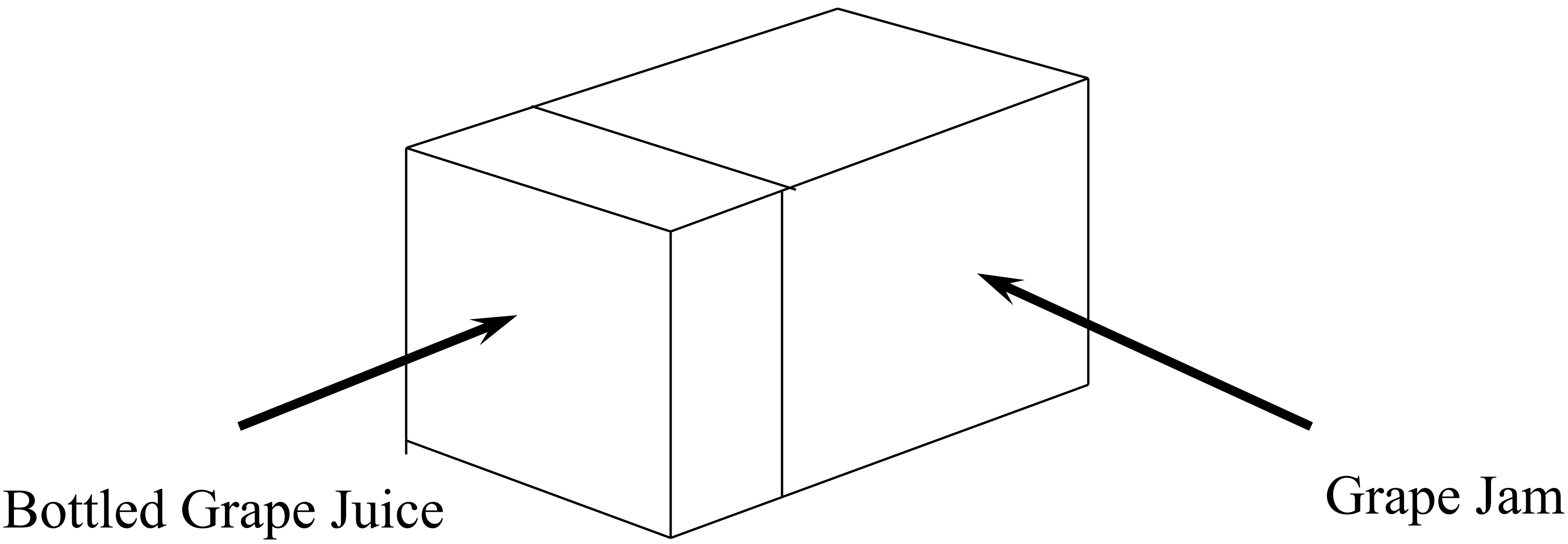
# Steps in Grape Juice Processing



# Planning and Material Management for Grape Juice (problem 1)

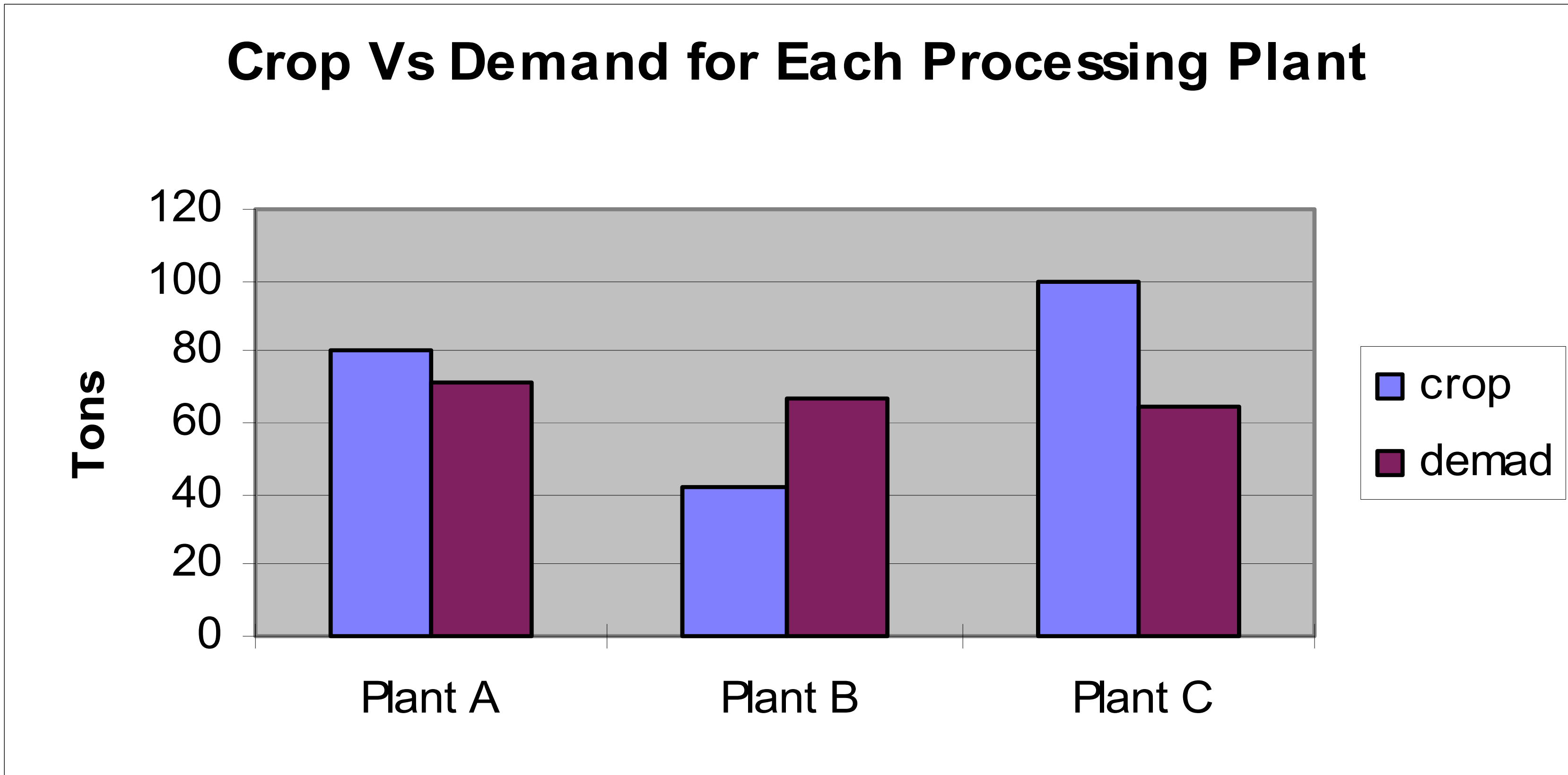
- **After harvest all grape juice becomes work in process**
- **Time lags between several important processing steps (settling, concentration, filtering)**
- **Welch's has a "state of the art" infinite capacity MRP system for decision making and materials management**

# The Total Grape Crop

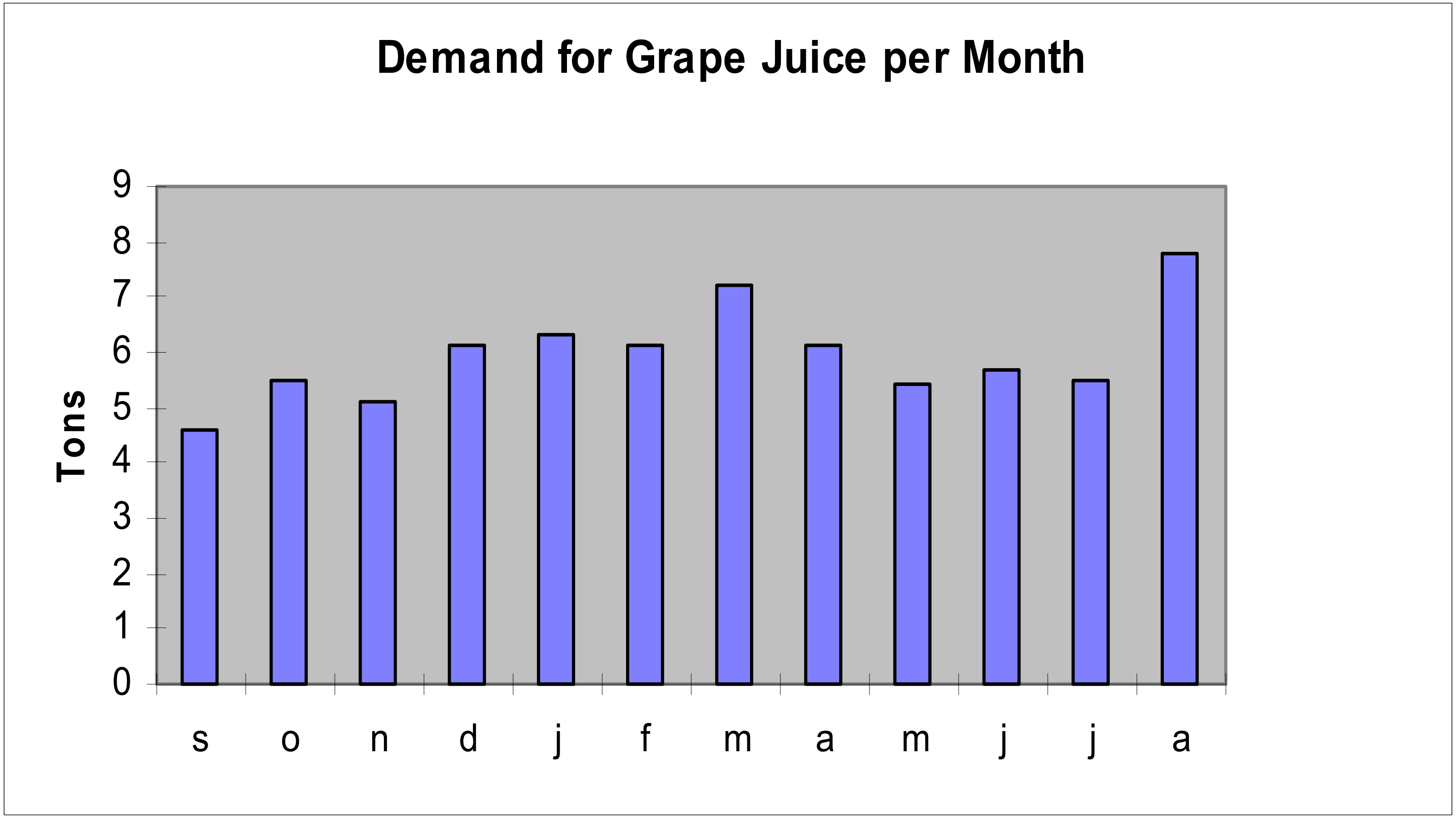



What is the proper allocation for each major product group?

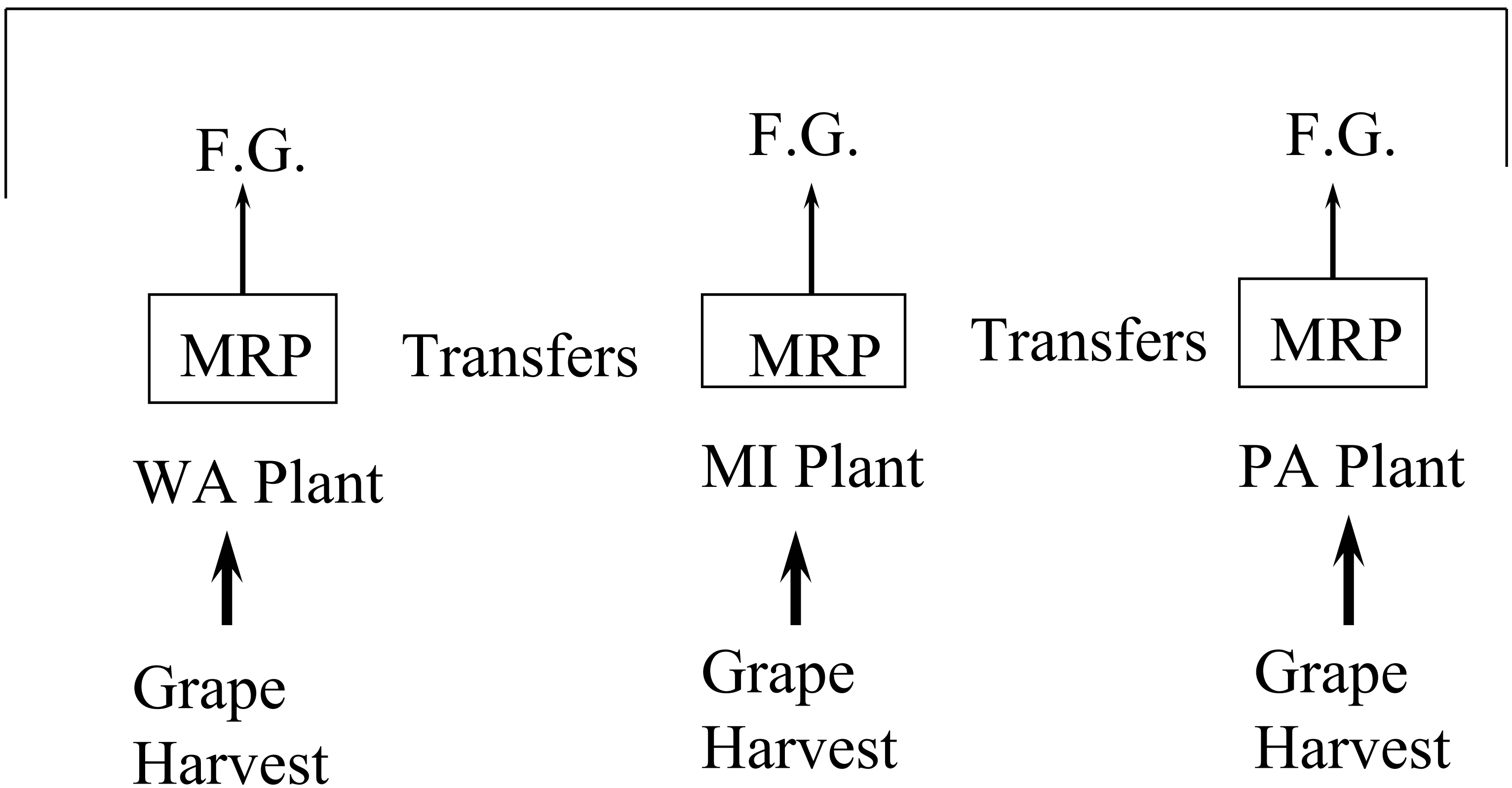
# Crop vs. Demand



# Demand for Grape Juice per Month



# Recipe/Transfer Coordination



# System Costs Include:

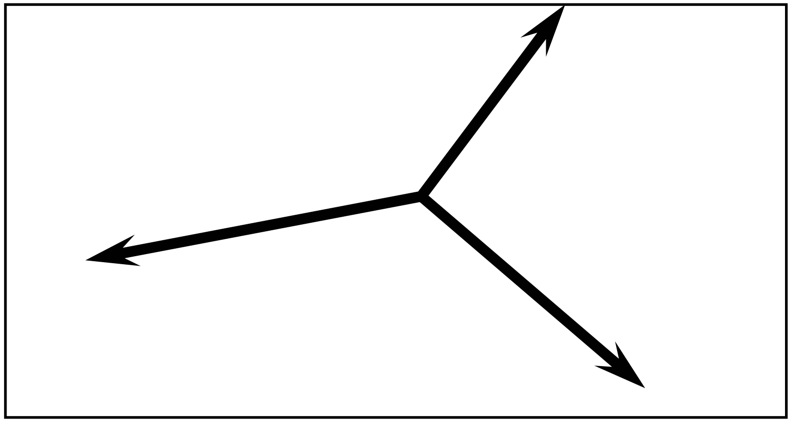
- Interplant transfers of grape juice
  - mode of transportation
  - timing of shipments
- Cost of recipe
  - blending of juice, quality attributes
- Inventory holding costs (carryover and crop storage)
  - space making
  - outside storage

# Grape Juice Quality Attributes:

- **Fruit solids (sweetness)**
- **Flavor**
- **Color**
- **Acid**
- **All attributes change with crop size and weather. We keep extensive records on the brix/acid ratio, color and flavor**

# Capacity Constraints

- **Transfer constraint - rate of transfer between plants, number of rail cars and location**
- **Carryover (new crop) and tank space availability**
- **Material balance constraint**



# Major Raw Material Decisions Include:

- Recipes to use for major product groups
- Transfers of grape juice between plants
- Control of carryover (year to year)
- Financial impact of recipe and transfer decisions on return per ton
- The mode of transportation (rail or truck) for transfers between plants

# *Summary*

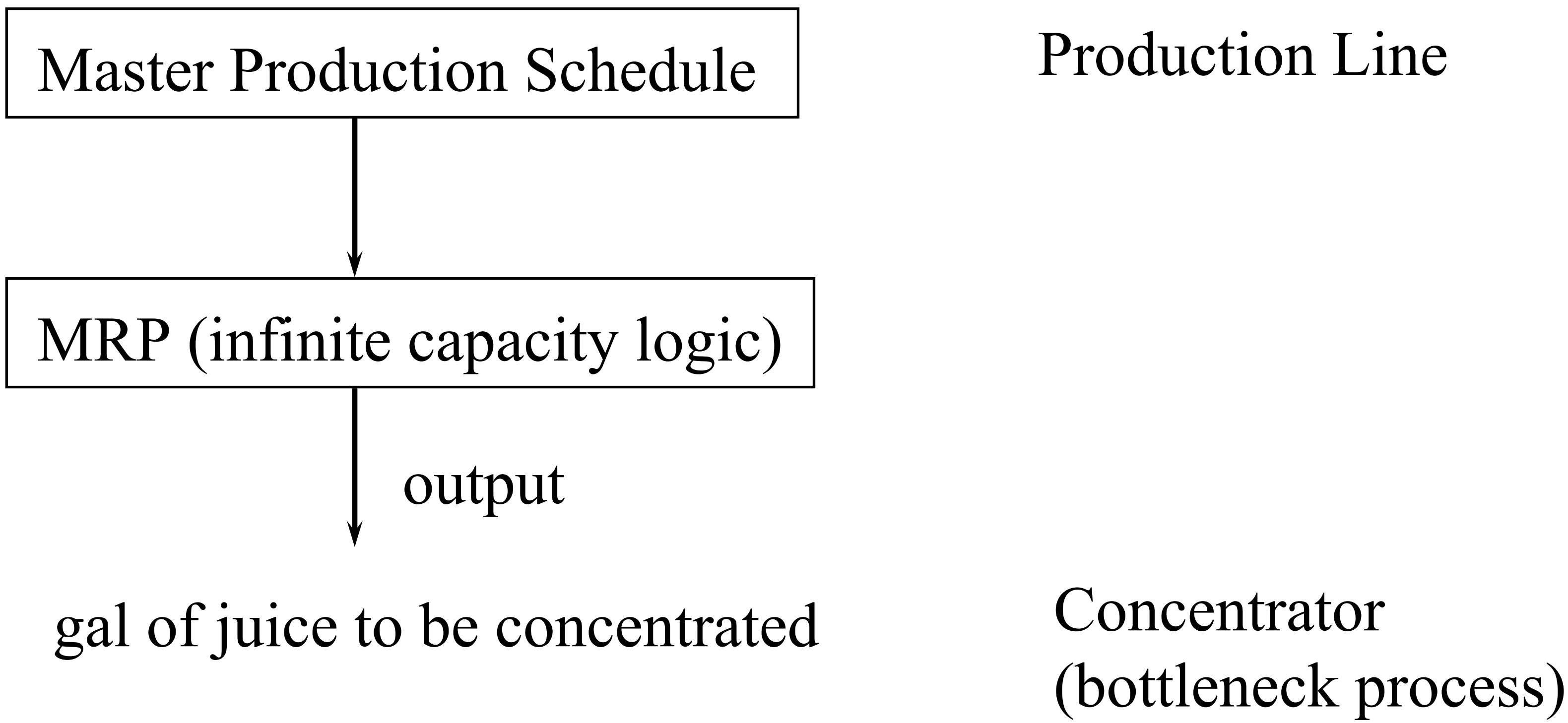
## Problem 1 - Raw Material Planning

- **Complex, dynamic system**
- **Supply seldom meets demand**
- **MRP does not account for capacity constraints or cost**
- **Current system has regenerative logic, requiring six hours per run**
- **Limited decision-making ability with current "state of the art" MRP system**

# Scheduling a Key Resource that Produces WIP (Problem 2)

- **Concentrate single strength juice**
- **From between five and twelve different types of juice to concentrate**
- **Set-up time and cost vary for each type of juice, at each plant**
- **Current MRP system has infinite capacity logic for lot sizing**

# Key Resource Deep in the Process Flow of Each Plant



# *Summary*
# Problem 2 - Scheduling dependent demand

- **Infinite capacity logic**
- **No optimal cost solution (trade-off between set-up and carrying cost)**
- **Single level, lot sizing problem under limited capacity**

# The Issues of CMRP

- Lot sizing with dependent or independent demand looks the same
- Trade-off between inventory carrying cost and set-up cost or between set-up cost and capacity (Umble, 1992)
- No traditional methods consider capacity
- Since 1980 researchers developed capacitated approaches

# CMRP Implementation Issues

- **Multi-level vs. single level**
  - **deep bills-of-material cause problems**
- **Large scale vs. small scale**
  - **math solutions require specialized knowledge**
- **WIP lot sizing vs. raw material lot sizing**
  - **a single lot sizing method often used**
- **Multi-plant vs. single plant**
  - **MRP was designed for single plant operation**

# Viability of CMRP in Practice

- **Capacity management is one of the most important issues to practitioners (Berry and Lancaster, 1992)**
- **Practitioners use the simplest lot sizing method, <u>lot for lot</u> (Haddock and Hubicki, 1989)**
- **Simple methods are poor performers (Choi, Malstrom and Tsai, 1988)**

# Why is CMRP Viable in the Process Industries?

- **Survey did not include process-oriented firms, no distinction between discrete and process-oriented mfg.**
- **Process industries reject MRP in favor of other methods based on process structure (Taylor and Bolander, 1994)**
- **An integrated supply chain requires finite capacity at each link**

# Traits of Process Manufacturing

- **Wide range of environments**
  - **continuous vs batch process**
- **No universal solutions**
  - **wide differences between different segments**
- **High customer service expectations**
  - **99% percent cases ordered vs cases shipped**
- **Dynamic demand**
  - **sudden changes in demand**

# Flat Bill of Material Structures and CMRP

- Single level - local optimal solution
- Modify existing MRP systems – heuristics
- Specific lot sizing methods - focus
- More chance for multi-plant CMRP - simplification of BOM structure
- V-shaped product families - influence system design

# Solution Methods for CMRP

- **Mathematical programming**
  - classic approach to capacitated problems
  - longest history of research
- **Heuristic (rule of thumb)**
  - few theorems in support of solutions
  - sometimes very specific to problem
- **Theory of constraints**
  - new view of manufacturing
  - no documented applications in the process industries

# CMRP and Mathematical Programming

- The "sifter" method (Dzielinski and Gomory, 1965)
- Multi-level lot sizing
- Harris Corporation - semiconductor sector
  - Leachman, Benson, Liu and Raar (1996)
  - replace infinite capacity MRP
  - decomposition solution method
- Several years before widespread use in the process industries

# CMRP and Heuristics

- Very quick solutions
- Testing under different conditions required
  - design of experiments
- The work of Allen, Martin, D'Itri and Schuster
  - 1997, 1998 and 1999
- Dixon-Silver heuristic (1981)
- Solve using Excel plus visual basic

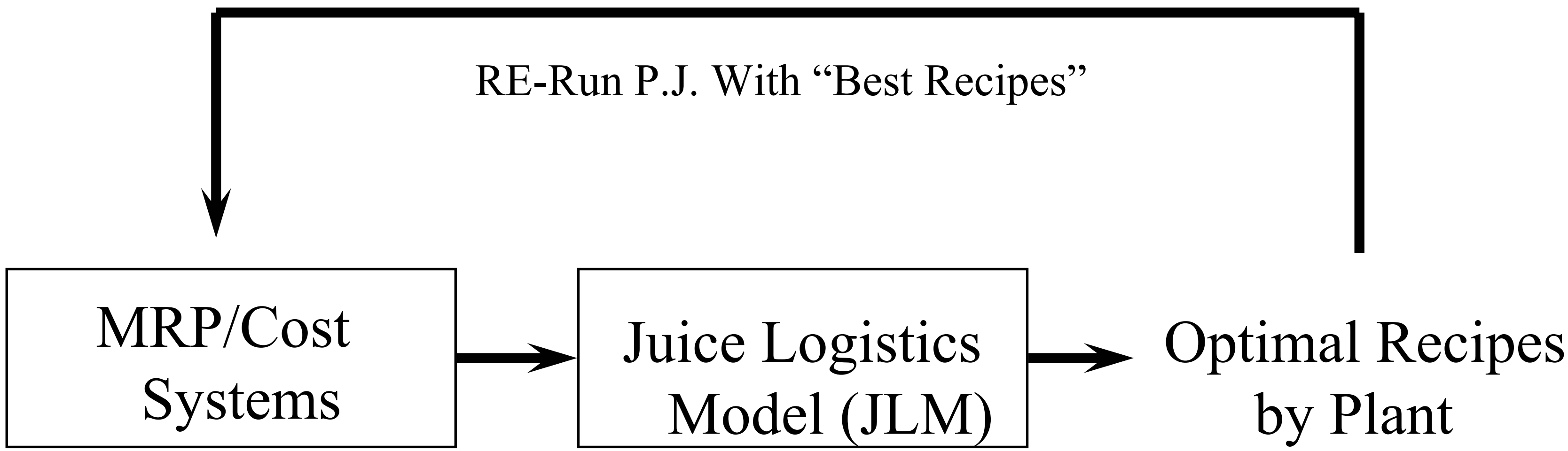
# Solutions Welch's Adopted to <u>Problems 1 & 2</u>

- **Adapt existing MRP and cost accounting systems using additional "auxiliary" models to achieve CMRP in practice (Geoffrion, 1976)**
- **Download data into spreadsheets from the mini-computer**
- **Use a combination of mathematical programming and heuristics as the "auxiliary" model**

# Solution
# Problem 1 - Raw Material Planning

- **An auxiliary model introduced that interacts with the MRP and cost accounting systems**
- **The Juice Logistics Model (JLM)**
- **Recursive solution method**
- **Formulated as a linear programming problem**
- **Spreadsheet optimizer (What's Best)**

# Recursive Solution Method




Total Tons by Product Group

A "Scratch Pad" for Aggregate recipes

Output from JLM

*Accurate Standards (Budgets)*

*Quick Solution*

*Best Recipes for MRP Based on Min. Cost and Sys. Constraints*

# 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)

***Given 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, where i = 12 (tons)

**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

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

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

(4) Tons sold minimum recipe

$$TS(i,j,k) \ge b(i,j,k)TU(i,j,k)$$ For all i,j,k

(5) Minimum ending inventory

$$EI(12,k) \ge MI(k)$$ 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

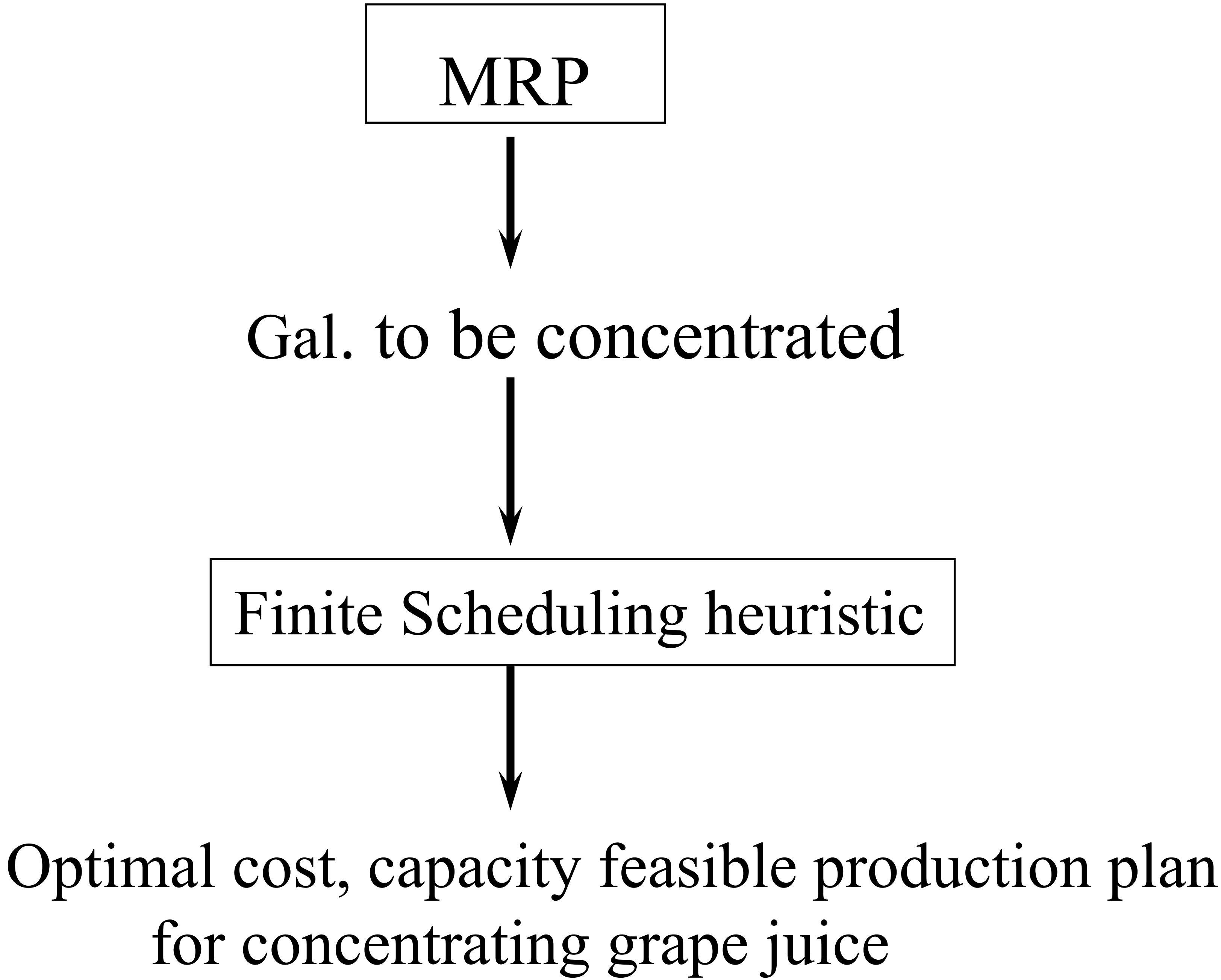
$$TO(i,k,m) = TI(i,m,k) \quad \text{For all i,k,m; } k \neq m$$

(8) Tons sold constraint for each plant

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

# Solution
# Problem 2 - Scheduling Dependent Demand

- **Heuristic solution - Allen, Martin and Schuster (1997)**
- **Embed heuristic into infinite capacity MRP system for capacitated lot sizing**
- **Use Excel spreadsheet for calculations**
- **The heuristic considers capacity, cost and is very quick**


MRP
Gal. to be concentrated
Finite Scheduling heuristic
Optimal cost, capacity feasible production plan
for concentrating grape juice

# Table 1

## TABLE 1 - Inputs to the Scheduling Heuristic

| 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 2

## Table 2

## Demand Forecast - Gal. of Concentrate Req. per Time Period

| 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 3

## Table 3 - Planned Production per Time Period in Gal.

| Item | Wk 1 | Wk 2 | Wk 3 | Wk 4 | Wk 5 | Wk 6 | Wk 7 | Wk 8 | Wk 9 | Wk 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Time Period | | | | | | | | | |
| 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 |
| 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

## Table 4 - Ending Inventory per Time Period in 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 | 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 |

# Implementation Issues

- **Support and software**
- **validity of the models**
- **end-used computing and programming**
- **The application of visualization to model formulation in spreadsheets**
- **Structured modeling (Geoffrion,1987)**

# Conclusion

- **CMRP will become a reality**
- **Practical methods exist to adapt MRP into a pseudo CMRP**
- **Next generation of MRP solutions will be defined by capacity**
- **More intensive use of mathematics in logistics and operations management**