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INTRODUCTION TO SUPPLY CHAIN SIMULATION

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ABSTRACT

Although a corporation does not own all of its supply chain, the entire chain is responsible for product delivery and customer satisfaction. As one of several methodologies available for supply chain analysis, simulation has distinct advantages and disadvantages when compared to other analysis methodologies. This tutorial will detail the reasons why one would want to use simulation as the analysis methodology to evaluate supply chains, its advantages and disadvantages against other analysis methodologies such as optimization, and business scenarios where simulation can find cost reductions that other methodologies would miss.

1 INTRODUCTION

In 1998, I wrote a paper called *The Value of Simulation In Modeling Supply Chains* (Ingalls, 1998), where I outlined my experience in bringing supply chain simulation to Compaq Computer Corporation in the late 1990's. A lot has changed in 15 years and this tutorial underscores the principles of supply chain simulation, how supply chain simulation is done, how it differs from supply chain optimization, and the basic structures that underlie supply chain analysis.

2 SUPPLY CHAIN OPTIMIZATION VS. SUPPLY CHAIN SIMULATION

Whenever I discuss supply chain simulation, I always feel like that I need to defend it against supply chain optimization in some way. I feel that way because the supply chain optimization crowd often sells itself as a solution to all of your supply chain analysis needs. If I present supply chain simulation to a group, it is likely that someone will stand up and tell me that optimization could have solved a given problem that I described during the talk. Because of this situation, I feel like *I am an agent for a great prospect named Supply Chain Simulation and he has some great skills that you need on your team*. Hopefully, you will consider giving *Supply Chain Simulation* a tryout when we are done.

2.1 Supply Chain Optimization is like *AutoTrader*

I have 6 sons and 5 of them have been driving age and I needed to buy them their first car. For the last 3 sons, I have found *AutoTrader* (www.autotrader.com) a great resource for finding their first car. Most of us know what *AutoTrader* does. *AutoTrader* allows the user to browse online for used and new cars. To quote their 2009 commercial (autotrader adHD, 2009), "When you search autotrader.com, we send more cars your way than anyone else in the world." So, how is supply chain optimization like AutoTrader?

First, AutoTrader has a seemingly infinite possible solutions. Supply Chain Optimization is the same way. Both have what we would call a large *feasible space*. It is all of the possible solutions that are viable for the business.

Second, AutoTrader and Supply Chain Optimization allow the user to define rules or guidelines (called *constraints*) to help with the search. In AutoTrader, the user selects year models, mileage limits, color, types of cars, etc. This helps narrow the search to a reasonable number of possible solutions. In the same way, supply chain optimization allows the user to put business rules into the model to define a smaller number of possible solutions. For example, a supply chain optimization defines the allowable structure of the supply chain. This structure will include sites that exist today and that may open in the future. It also includes customer sites and supplier sites. It includes which products (or possibly product groups) are included in the optimization. In addition, there may be many rules that must be followed. For example, the optimization will likely have a rule that all of the demand must be met. It may have rules on maximum and minimum inventory levels at distribution centers. It is likely have rules on the maximum amount of production that is allowed. These are just a few of the possible rules, and all of these rules narrow the possible solution to the problem.

Third, once the rules are put into place, both AutoTrader and supply chain optimization have to come up with an answer. To be more precise, the answer is considered the *very best answer* that can be achieved given the *feasible space* and the *constraints*. How the two come up with an answer is somewhat different. AutoTrader has you, the user, making the decisions. In the commercial, the woman buying the car says, “That’s the one.” In supply chain optimization, a mathematical function called the *objective function* determines the best answer. Typically, the objective function is a *find-the-least-cost* or *make-the-most-profit* objective. Either way, both are considered the *best* solution out of a very large number of *possible* solutions.

2.2 Supply Chain Simulation is like a *Test Drive*

When Dodge introduced the 2011 Charger, they came out with a great commercial. Picture a Charger driving down a rain-soaked city street and listen to the announcer say, “Did you hear about the car company test driving cars on the internet? You just logon, click ‘drive’ and hit the space bar to accelerate. All from your living room. That’s absurd. This is the all new 2011 Dodge Charger, available for real test drives.” The driver in the commercial hits the gas and the Charger revs up and moves quickly down the street.

Why do we *test drive* a car? Simply, there are just some things that *choosing the car* will not tell you. How does the car accelerate? How does it brake? How does it handle certain driving conditions? Is it a rough ride or a smooth ride? In essence, does the car perform well under *real-world conditions*?

Supply chain simulation is like a test drive. There are *real-world conditions* that the optimization will not address. First and foremost, supply chain optimization cannot address variance, or random conditions. Things like random demand, unreliable suppliers, machines that break down, and trucks that are late. Supply chain simulation can model all of these issues.

3 MANAGEMENT-SPEAK

When we talk to management about modeling, they typically do not have a management science or operations research background. Typically, they have a business background. Because of that difference, I often find that certain words that I might use in my classes are used differently in the business environment. As such, there are two words I never use in mixed company (academics and industry people) - *Optimization* and *Simulation*. I will use the word *Model*, but I have to be careful. Let’s say that you have a very dynamic supply chain that you want to analyze. What does your VP think when you tell him...

- “I am going to model your supply chain.”
- “I am going to optimize your supply chain.”
- “I am going to simulate your supply chain.”

The difference between what an academic thinks and what your VP thinks can be quite different. Table 1 outlines the differences between the two.

Table 1: The Differences Between Your VP and The Academic.

	Your VP	**The Academic**
Model	MRP and/or Excel	Any mathematical or logical formulation
Optimize	An efficient system in spite of real world problems	The best alternative of all mathematical formulations
Simulate	A MRP simulation	A detailed computer model that mimics the real system

First, the word *model*. If you are in a manufacturing environment, your VP will think that a model is either an Excel model or a MRP instance. Both of those are considered models and both are used for analysis. The academic will define a model as any type of mathematical or logical formulation. As such, it can be a linear program, a non-linear program, a continuous simulation, a discrete-event simulation, etc. Any of those are legitimate models.

Second, the word *optimize*. This is where the VP and the academic very often talk past each other. I, as an academic knows what an optimal solution consists of. For optimization models, the optimal solution is the best solution. As a matter of fact, I know that it is *impossible* to find a better solution based on the objective function. That is what it mean to an academic to optimize.

To a VP, to *optimize* means to make something as efficient as possible *despite all of the business issues*. So, even if the trucks are late or machines break down, we need to have an efficient supply chain.

Third, the word *simulate*. Typically, if you are in a manufacturing environment, a planning manager will use the word *simulate* to mean a MRP simulation. That is about the only time you will hear the word simulate used. To the academic, though, a simulation is a detailed computer model that has the necessary level of detail to mimic the key business process under study.

4 THE TWO MOST IMPORTANT QUESTIONS

There are two important projects that I ask with every project. First, “What question(s) are you trying to answer?” and second, “What constitutes a good answer?” If these two questions are addressed properly, then the answers will push the analysis in a given direction and will determine the tools needed to have a satisfied customer.

4.1 What Question(s) Are You Trying To Answer?

First, an example of “What question are your trying to answer?”

- This project will analyze the supply chain of all server products currently produced in Europe for consumption in the Asia-Pacific region and analyze the alternative of moving the production of those products to Singapore. Which of these two alternatives increases customer on-time delivery and corporate profits?

This question is critical because it focuses the project on the real problem. In this case, we state the current situation (server products produced in Europe and consumed in Asia-Pacific), its alternative (moving the production to Singapore) and the metrics we are going to use to evaluate the project (on-time delivery and corporate profits).

This question should start every presentation. It gives a clear understanding of the project and reminds the client which question(s) you are trying to answer. If the question changes, then the model and the approach could change as well.

4.2 What Constitutes A Good Answer?

The second question is "What constitutes a good answer?" The answer to "What constitutes a good answer?" is focused on the organizational issues involved. This answer should never show up on any PowerPoint presentation, but you better know the answer.

There are two key issues that must be part of the answer to his question. First is the due date. You have to know when the answer is still valuable to the client. The second is what I call the "burr under the saddle" or "what is keeping the VP awake at night" answer. This is often unspoken, but you need to understand it. It is the real reason why this project is important to the company and, if you address the "burr under the saddle," you will be very successful.

In addition, the senior person on the client team (usually a VP or director) must be able to understand the basics of the process you are using to perform the analysis. This can be difficult, but if the VP does not have a basic understanding of the process, it is difficult to get buy-in to the solution.

5 A SIMPLE SUPPLY CHAIN EXAMPLE

Figure 1shows a pretty simple supply chain problem.

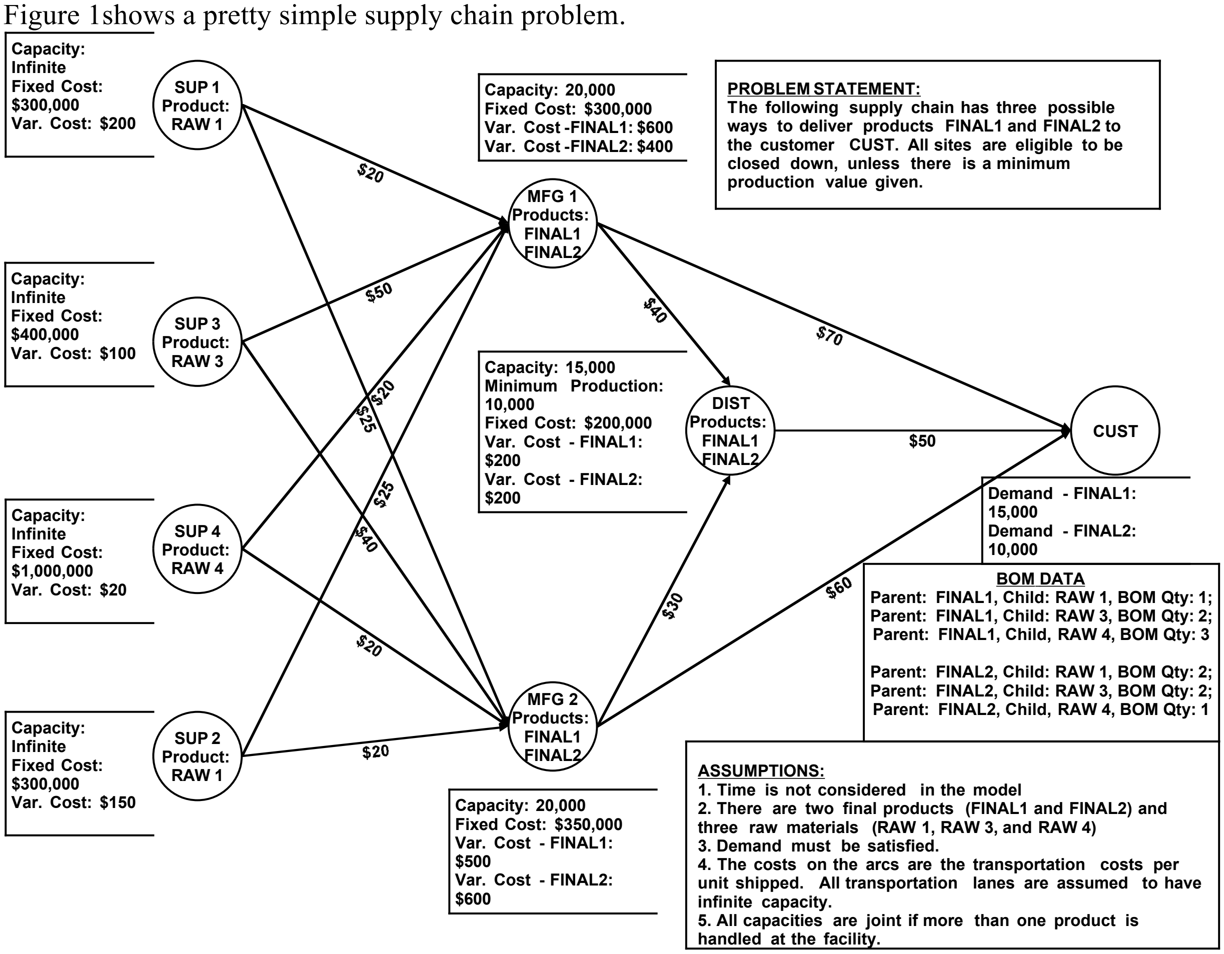

Figure 1: Simple Example Supply Chain Problem.

This example has the fundamental structure of a typical supply chain problem. Actual supply chain problem can be much more complex with different types of capacities and costs as part of the problem. The elements of this problem include:

1. Products

   (a) There are two final products: FINAL1 and FINAL2
   (b) There are three raw materials: RAW1, RAW3 and RAW4.
2. Sites
   (a) The following sites are in the model: CUST, DIST, MFG1, MFG2, SUP1, SUP2, SUP3, and SUP4.
      (i) CUST is the customer site that represents the customers receiving the product.
      (ii) DIST is a distribution center.
      (iii) MFG1 and MFG2 are two different manufacturing sites.
      (iv) SUP1-SUP4 are four different supplier sites
3. Transportation
   (a) Each path (or line) in Figure 1 represents a valid transportation lane from one site to another. The amount shown on the path is the unit transportation cost for the product that is shipped on that transportation lane.
4. Demand
   (a) Each FINAL product has a demand that should be met.
5. Bill-of-Material (BOM)
   (a) For each final product, there is a bill-of-material that consists of different RAW products. These products are assembled in the MFG sites.
6. Site Capacities
   (a) Each site has a capacity, which in this case, is the maximum quantity that can be produced or shipped from this site in a given time period. In actual supply chain models, capacities are usually much more complex.
7. Minimum Production
   (a) The DIST site has a minimum production quantity. This is the minimum that the site must ship. If a MFG site had this constraint, it would be minimum production at the site.
8. Fixed Costs
   (a) Each site has a fixed cost. The fixed cost is applied if the site is used at all.
9. Variable Costs
   (a) Each site/product combination has a variable cost at the site. This cost is applied if the product is produced or stored in a site.

5.1 Example 1: Can We Characterize Our Total Supply Chain Costs?

5.1.1 Problem Statement

In the following sections, we are going to take this basic supply chain problem and address it differently based on *The Two Most Important Questions.* Let's assume that the questions and answers are:

- What question(s) are you trying to answer?
  - Can we characterize our total supply chain costs and structure?
- What constitutes a good answer?
  - Any answer is good because the management does not understand where supply chain costs are occurring.

If these are the answers to the two questions, then we can answer this address this questions by simply building a spreadsheet that calculates the current cost of the supply chain. However, the current data is insufficient to actually calculate a supply chain costs. We have to add in additional information on what percentage of the product do we get from which sites. In some companies, this is called *sourcing*. In others, I have heard the term *deployment*. This sourcing plan reflects either the current situation or the company strategy on which products will be built in which sites and which suppliers the company will use for raw material. In this example, we will make the following sourcing decisions:

- We want to keep the DC active, so 50% of all products will go from the DC to the customer.
- The remaining 50% are split between the 2 manufacturing sites
- The DC receives products from evenly from both manufacturing sites
- The manufacturing sites receive raw material RAW1 from the closest supplier

5.1.2 Solution

The solution to Example 1 is shown in Figure 2.

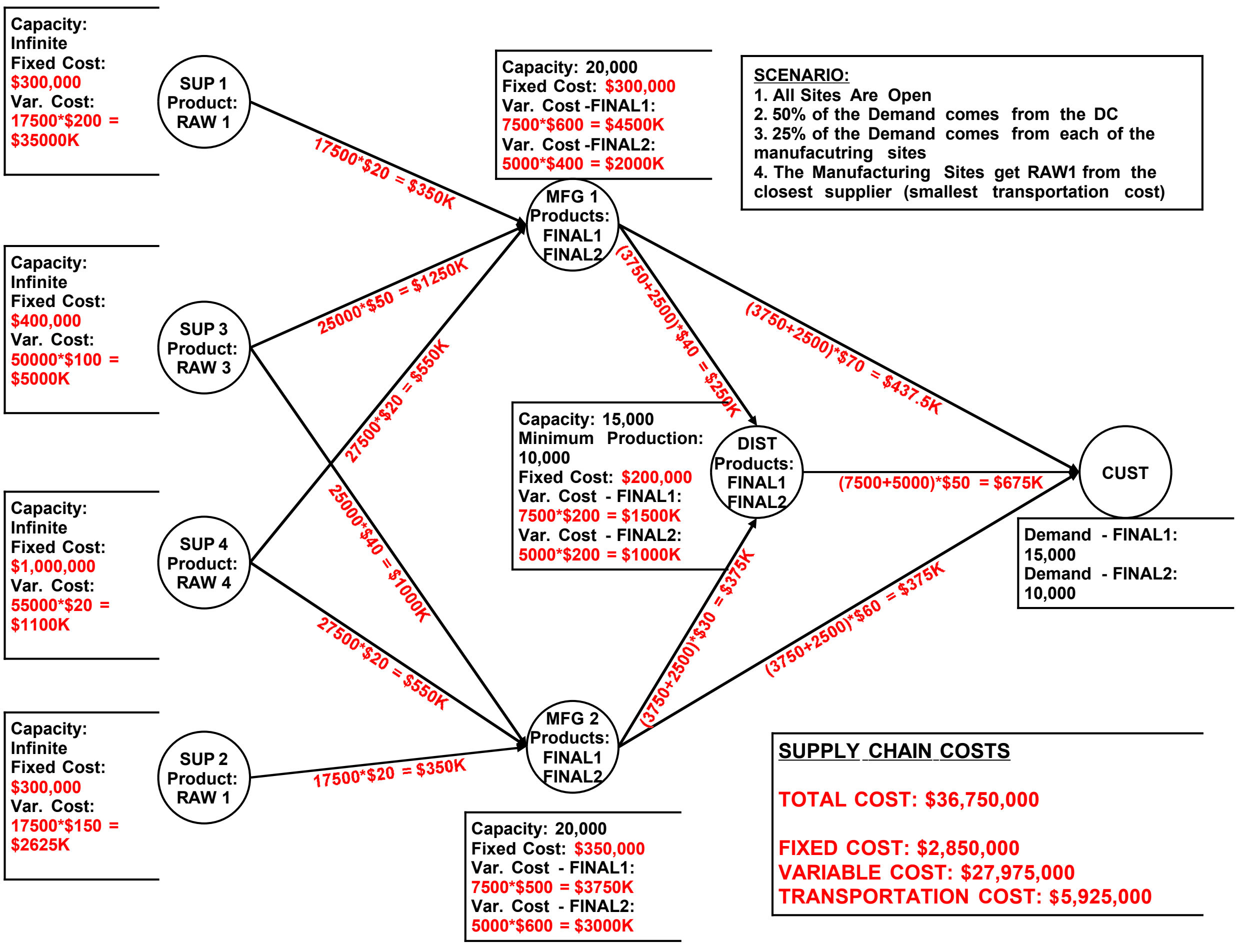

Figure 2: Example 1 Solution.

Obviously, the sourcing percentages can be changed to reflect different scenarios that the management would want to look at. If we adjusted the sourcing percentages enough and respected the capacities and minimum production, we could get a solution that is a lower cost. However, that was not the focus of this particular project.

5.2 Example 2: Can We Determine The Supply Chain Structure That Costs The Least Amount Of Money?

5.2.1 Problem Statement

For the second example, the answers to the most important questions change. Now the answer to the most important questions are:

- What question(s) are you trying to answer?
  - Can we determine the supply chain structure that costs the least amount of money?
- What constitutes a good answer?
  - The management believes that our supply chain is inefficient and costs can be cut if we get the right suppliers and redeploy product in the supply chain.

The management is looking for something different with these answers. The focus of the problem has changed from evaluating the supply chain cost to *finding the least cost* supply chain configuration. When the question implies a *least cost* or *maximum profit* solution, then the best analytical approach is *mathematical optimization*.

The optimization model itself is a superset of the supply chain. It includes:

- All of the possible locations
- All of the possible transportation routes
- All of the necessary capacities
- All of the necessary costs, including site opening/closing costs.

The model then chooses the "best" supply chain configuration based on some combination of cost, profit and time.

In mathematical optimization, the algorithm manipulates the *decision variables* in such a way to *minimize the cost* without *violating the constraints.* In this particular model, the *decision variables* are the amount of product that is shipped from one site to another. If we know how much product is being shipped from one site to another, then we will know how much is being produced in each site and which products are shipped to meet the demand.

The *constraints* in the model are equations that we had in the spreadsheet to make it work. For example, there is an equation to make sure the demand for product FINAL1 is met. It is

$$Shipped(MFG1, CUST, FINAL1) + Shipped(MFG2, CUST, FINAL1) +$$
$$Shipped(DIST, CUST, FINAL1) = DEMAND(FINAL1)$$

Another type of a constraint is a capacity constraint. Below is the capacity constraint for site MFG1:

$$Produced(MFG1, FINAL1) + Produced(MFG1, FINAL2) \leq Capacity(MFG1)$$

The formulation of the model is fed to an optimization program and the program finds, in this case, the least cost configuration of the supply chain.

5.2.2 Solution

The solution to the optimization is shown in Figure 3. As can be seen, this solution is substantially lower cost than our spreadsheet solution. At a high level, the difference between the two models are shown in Table 2.

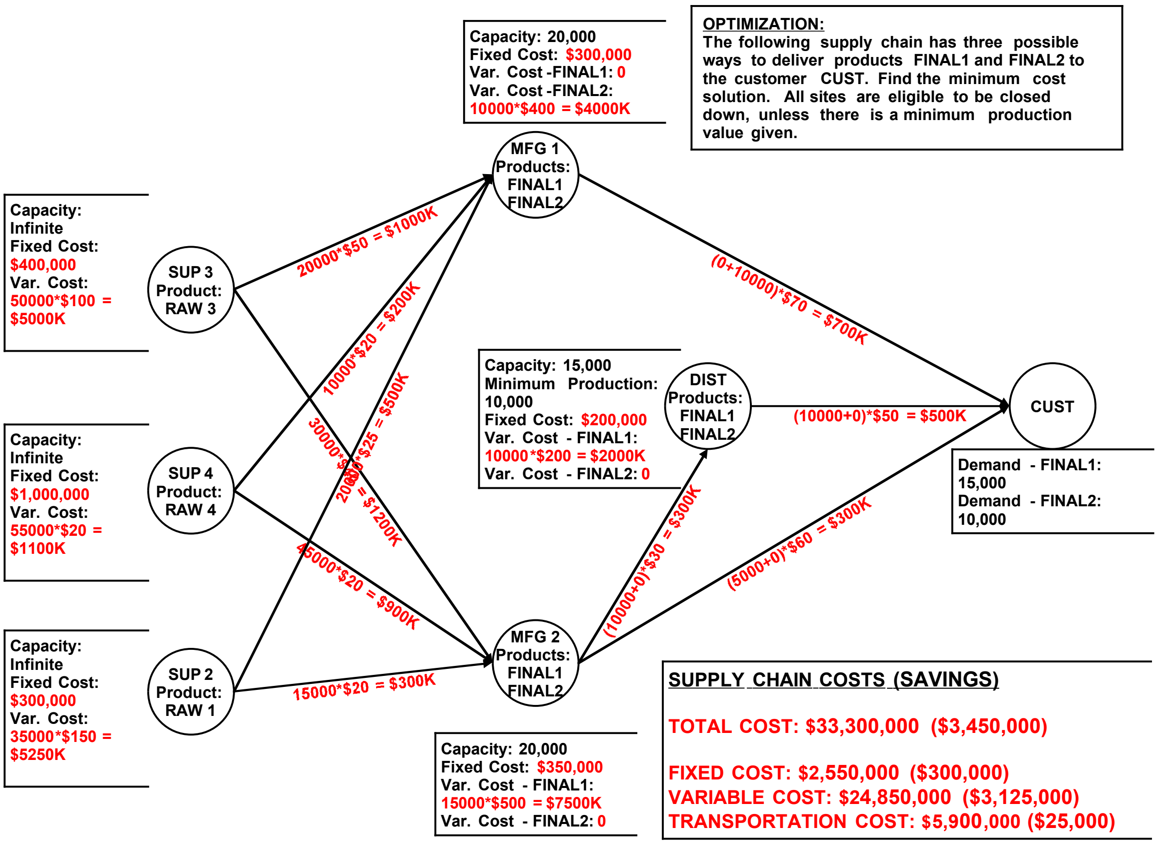

Figure 3: Example 2 Solution.

Table 2: Comparison of Example 1 and Example 2.

Metric	*Example 1*	*Example 2*	*Improvement*
Fixed Cost	$2,850,000	$2,550,000	$300,000
Variable Cost	$27,975,000	$24,850,000	$3,125,000
Transportation Cost	$5,925,000	$5,900,000	$25,000
Total Cost	**$36,750,000**	**$33,300,000**	**$3,450,000**

Also notice what the optimization decided to do with the structure of the supply chain. First, the supplier SUP1 is no longer part of the supply chain. All RAW1 material is now sourced from SUP2. The model has also decided to keep the DIST site at its minimum of 10,000 units. Also, FINAL1 and FINAL2 manufacturing is now dedicated to different manufacturing sites. FINAL1 is now produced in MFG2 and FINAL2 is produced in MFG1.

This is a significant change to the supply chain. The management is now in the situation to accept this change or modify it. If there are management issues that makes this solution non-implementable, then the model will need to be changed to reflect management realities and re-run.

5.3 Example 3: How Can We Reduce Inventory And Not Hurt Customer Satisfaction?

5.3.1 Problem Statement

This last example is different because it bring some different metrics into the discussion. The answers to the two questions are:

- What question(s) are you trying to answer?
  - We are carrying several weeks of inventory in the supply chain. Do we need that much inventory? How will decreasing inventory effect customer satisfaction?
- What constitutes a good answer?
  - We need to drop more costs by dropping inventory while not hurting customer satisfaction.

Immediately, we see two items that we have not discussed in the previous two examples – inventory and customer satisfaction. What makes this example different than examples 1 and 2 is that these metrics are effected by the *dynamics* of the supply chain. Since we have unpredictable demand and/or supply, we need to store inventory. Also, customer satisfaction is primarily concerned with running out of inventory when unexpected customer orders arrive. Since these metrics are effected by the *dynamics* of the supply chain, we must use *simulation* instead of *optimization* to analyze the supply chain. Simulation cannot find an optimal solution, so instead, the analyst must create scenarios to analyze.

In order to address the dynamics of the system, we need to add more structure to our model, including:

- Production cycle times
- Transportation lead times
- Random demand
- Revenue for product sold
- Inventory levels at the DIST site
- Raw Material inventory at the manufacturing sites
- Daily capacities instead of annual capacities

5.3.2 Alternative 1

Alternative 1 takes the optimal solution of Example 2, and then puts the realistic, dynamic attributes of the business into the simulation model. Because the simulation is more realistic and mimics the real system, we had to collect more data and we discover the following:

- Revenue is $1500/unit (expected $37.5M)
- Daily Demand is random that averages 15000/365 units per day for FINAL 1 and 10000/365 units per day for FINAL 2.
- Finished Good Inventory at the DC: 2 weeks
- Production Cycle Time in Manufacturing: 3 days.
- Raw Material Inventory at Manufacturing Sites: 2 weeks
- Inventory Carrying Costs: 50%
- Transportation Times: Varies based on the source and the destination.
- Capacities: Daily Capacities are Site Capacities/365.

After adding this data to the model, we decide to run 30 different 1-year models with different random demand to determine how the system performs.

Table 3: Example 3, Alternative 1 Solution.

	Alternative 1		
Statistic	***Mean***	***Min***	***Max***
Revenue	$37.2M	$35.8M	$39.1M
Costs	$33.1M	$31.9M	$34.5M
Profit	$4.16M	$3.89M	$4.52M
Inventory Value	$2.72M	$2.71M	$2.74M
ICC	$1.36M	$1.36M	$1.37M
Profit w ICC	$2.80M	$2.53M	$3.16M
Missed Revenue	$181K	$15.0K	$330K
Missed Demand 1	0.27%	0.00%	0.66%
Missed Demand 2	0.80%	0.02%	1.74%

Table 3 shows the solution to the 30 simulation runs. The *Mean* column is the average of a given statistic for the 30 different runs. For example, the mean of the Revenue statistic is the average revenue collected over the entire year. The *Min* column is the smallest revenue of the 30 runs and the *Max* column of the 30 different runs.

Notice the different type of statistics that we have collected from the simulation. First, we have inventory statistics for the system. Second, we have customer satisfaction metrics such as *Missed Revenue, Missed Demand* percentage for FINAL1 and also *Missed Demand* percentage for FINAL2.

Analyzing the outputs, we see that we are carrying a lot of inventory ($2.72M on average) and because of our high inventory carrying costs, this is taking a lot of money from the profitability of the firm. Also, we see that we are meeting almost all of the customer demand. Obviously, we might want to make a trade-off: lower inventory and slightly higher missed demand.

5.3.3 Alternative 2

Since it is obvious that we are carrying a lot of inventory (approximately 13.6 financial turns/year) and meeting the customer demand, we have been tasked by management to increase inventory turns at least 18. Let's run a scenario were the finished good and raw material inventories are cut to 2 days and see what we get.

Table 4 gives the results of Alternative 2 and a comparison to Alternative 1.

Table 4: Example 3, Alternative Comparison.

	Alternative 1			***Alternative 2***				
Statistic	***Mean***	***Min***	***Max***	***Mean***	***Min***	***Max***	***Change***	***%Change***
Revenue	$37.2M	$35.8M	$39.1M	$36.2M	$35.2M	$37.1M	($1.00M)	(3.0%)
Costs	$33.1M	$31.9M	$34.5M	$31.8M	$31.0M	$32.6M	($1.30M)	(3.8%)
Profit	$4.16M	$3.89M	$4.52M	$4.32M	$4.07M	$4.62M	$0.16M	3.9%
Inventory Value	$2.72M	$2.71M	$2.74M	$1.71M	$1.68M	$1.74M	($1.01M)	(37.4%)
ICC	$1.36M	$1.36M	$1.37M	$853K	$838K	$868K	($0.51M)	(37.4%)
Profit w ICC	$2.80M	$2.53M	$3.16M	$3.47M	$3.22M	$3.77M	$0.67M	24.0%
Missed Revenue	$181K	$15.0K	$330K	$1.42M	$0.35M	$2.38M	$1.24M	682%
Missed Demand 1	0.27%	0.00%	0.66%	3.30%	1.13%	5.95%	3.03%	1100%
Missed Demand 2	0.80%	0.02%	1.74%	4.39%	0.76%	9.05%	3.59%	452%

This results of Alternative 2 is interesting, and from a dynamics standpoint, it makes perfect sense. First, consider what we did - we lowered inventory. What would we expect from lowering the inventory? We would expect to miss more customer demand. Missing more customer demand means lower revenue. That is exactly what we see. On average, missed demand for FINAL1 goes from 0.27% to 3.3% and missed demand for FINAL2 goes from 0.8% to 4.39%. Also, revenue drops from $37.2M to $36.2M which is a drop of 3%.

We also lower the costs of the supply chain. We lower the cost because we do not have to buy as much product to maintain the higher inventory levels. Also, since the target inventory days are lower, we can place orders to the suppliers later in time and avoid some of the bullwhip effect. The cost drops from $33.1M to $31.8M which is a drop of 3.8%. Since the reducing in cost is larger than the reducing revenue, the profit (not including ICC) increases by $160M, or 3.9%.

Since we lowered inventory, we would expect to see that reflected in the solution and we do. Inventory drops over $1M (37.4%) and Inventory Carrying Costs drop by $670K. This increases the overall profit (including ICC) by $670K, which is an outstanding 24% increase!

5.3.4 Conclusions About Example 3

In this small example, we show that the answers are not straightforward. You can

- Improve overall profitability (24%)
- Reduce inventory targets (21.2 turns vs. 13.6 turns)
- Make more customers dissatisfied (3.74% missed demand vs. 0.48% missed demand)
- Miss more revenue ($1.42M vs. $181K)

So, which alternative would you choose. It is not obvious which one is best. The decision makers, though, have sufficient information to understand the impact of the change in Alternative 2.

Unlike optimization, which takes a static model and gives the best solution, simulation simply gives realistic alternatives to consider. This is the purpose of a simulation. It gives the ability to analyze the actual dynamics of the system, but you must manage the scenarios and make rational business decisions based on the results of each scenario yourself.

5.4 What Type Of Analysis Should We Choose Based On *The Two Questions*

Understanding the impact of the two questions is critical for the proper analysis of any system. For the first question, “What question(s) are you trying to answer?” you need to look at the question and what metrics are either mentioned directly or implied in the answer. If you can choose from a large number of static solutions, then the best tool is optimization. If you need to evaluate dynamic conditions, such as customer satisfaction or varying customer demand, then you need to use simulation.

For the second question, “What constitutes a good answer?” you need to listen to what the management is really saying. If you listen, they will tell you what is keeping them awake at night. They will also let you know when they need to get the answer to their questions. The timing of the answer *may* impact the decision on which analysis tool to use. For example, if the answer is needed in one week, it is unlikely that an optimization or a simulation can be performed in that timeframe.

6 BUSINESS SITUATIONS WHERE OPTIMIZATION WILL NOT WORK

Whenever I present this topic in a conference, especially if optimization people are in the room, I get challenged on the veracity of what I am about to say. What is it that upsets people so much? I say, “There are business situations where optimization *will not work*.” And it is true. There are business situations where optimization will not work. Below, I discuss three key business issues that simply cannot be handled with optimization.

6.1 Demand Forecast Changes And Forecast Error

The first business situation where optimization will not work is the business process where *demand forecast changes over time*. The primary reason for the bullwhip effect and the erratic movement of material in the supply chain is the fact that the demand forecast changes over time (Ingalls, et al., 2005). Every MRP/ERP process makes decisions based on the current demand forecast and reevaluates its decisions when the demand forecast changes.

As an example, let us assume that the MRP system is re-run on a weekly basis at your company. This week, we have a 6-month weekly demand forecast. Assume that we have a supplier whose lead time is 12 weeks. When this is the case, a purchase order is sent to the supplier based on the demand forecast 12 weeks out. For simplicity, let's assume that the supplier has no other purchase orders active, the demand 12 weeks out is 100 units, and our purchase order is for 100 units to arrive in 12 weeks.

A week passes and a new demand forecast in place. The demand that was 100 units 12 weeks out last week is now 90 units and 11 weeks out. How does the MRP system respond to this new data? It cannot do anything, except perhaps issues a purchase order change notice for 90 units instead of 100. That costs money. The other alternative is to ignore the drop and end up with 10 additional units in inventory with no demand against it. That is obsolescence.

But what if the demand went up? The demand that was 100 units 12 weeks out last week is now 110 units and 11 weeks out. The MRP system wants to issue an expedited purchase order for an additional 10 units to arrive in 11 weeks. That is expensive. The alternative is to create a purchase order for 10 units to arrive in the normal lead time, which is 12 weeks. That means that the customer demand of 110 will not be satisfied on time. Only 100 units will be satisfied on time. This hurts customer satisfaction.

In general, If the demand forecast is up, the chain tries to produce more product in order to fill inventories up to their proper levels. This can mean overtime expenses, expediting charges, and other charges. If the demand forecast is down, then manufacturing sites go idle, materials already in inventory go obsolete, and costs already in the chain have to be absorbed. Only simulation can address this type of supply chain dynamics.

6.2 Downside Risk For Wall Street

When corporate management looks at almost any decision, there are two primary considerations: profitability and downside risk. Profitability is easily handled by optimization, but that is not the case for downside risk. For any set of decisions, there are conditions outside of the company's control that can effect the benefits of those decisions. Profit can increase or decrease simply because of the uncontrollable random effects.

The reason that corporate management is worried about downside risks is because the company stock gets hammered if the company misses Wall Street analysts projections. The process works something like this:

1. The company announces earnings and makes "forward looking statements".
2. Based on the "forward looking statements" and other information, the Wall Street analysts estimate the company's earnings in the future, starting with the next quarter.
3. The stock price goes up (or down) based on the future earnings estimates.
4. The company announces the next quarter's earnings.
   (a) If the company does not meet the earnings estimates, the stock price plummets.
   (b) If the company meets (or even exceeds) the earnings estimates, the stock stays stable.
5. Go to Step 2.

There is just no incentive to exceed the earnings estimate, but there are large disincentives for missing the earnings estimate. Consider Figure 4. Which of the 4 scenarios do you think a senior manager will pick? Obviously, scenarios 3 and 4 are much higher profit. Scenario 4 has a slightly lower average profitability, but it has a smaller downside risk. The corporate manager would pick scenario 4. Optimization simply cannot evaluate the downside risk because of dynamic conditions.

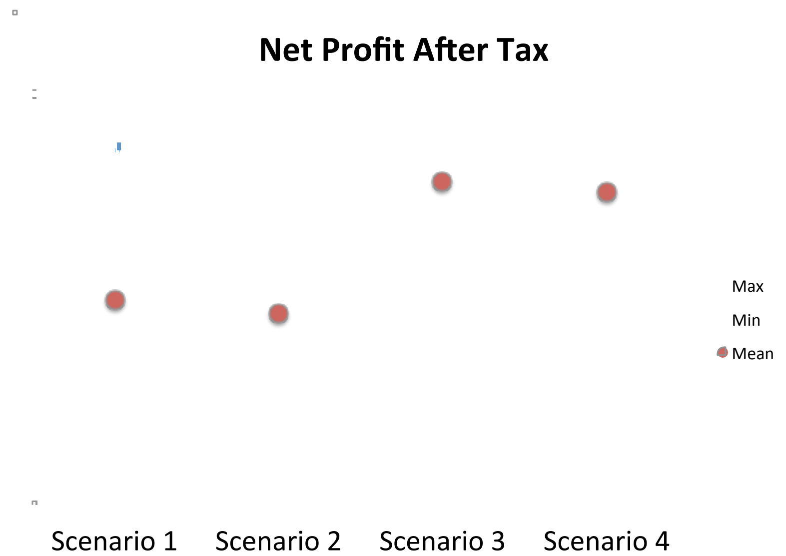

Figure 4: Solutions from Different Scenarios.

6.3 Too Complicated To Optimize

This is where I usually get beat up by the optimization crowd. They cannot accept that there are certain business issues that are simply too complicated to optimize. Since simulation is a programming system, simulation can program in the most complicated of business rules.

The fact is that many business rules cannot be reduced to a formula. These rules are usually rule-based or some sort of prioritized scheme to run the business. A good example is a prioritized selection of suppliers, even though some secondary supplier may be cheaper. The optimization will choose the secondary supplier because of cost. The business cannot choose the secondary supplier unless certain extreme business conditions occur. Optimization cannot handle that situation.

The second item that is too complicated to optimize is *variance, variance, variance*. From demand forecast changes, supplier lead time variance, unreliable resources in the supply chain, this type of variance simply cannot be reflected in an optimization model. The only practical way to model these issues is to use simulation.

7 BUSINESS SITUATIONS WHERE SIMULATION WILL NOT WORK

Simulation is an excellent tool when it comes to analyzing *the design* of a supply chain after the optimization has chosen the optimal supply chain structure, but it is not the right tool for every supply chain analysis application. Below, I want to outline a couple of examples where simulation is just the wrong tool for the work and why optimization is clearly the better choice.

First, optimization is clearly better when you are performing supply chain planning. The characteristics of supply chain planning include a multi-period model that deals with all of the SKUs, customers, distribution centers, manufacturing facilities, suppliers, etc. This large scale is offset with the fact that the model is not making any design decisions. In most cases, this model is so large that modelers must avoid any modeling constructs that would change the model from a linear program to a mixed-integer program so that the model runs in a reasonable amount of time.

Second, optimization is clearly better when you are performing supply chain MRP capacity analysis. In typical MRP analysis, planning is done without regard to capacity limitations at each of the facilities. If an optimization is used instead, the MRP run will determine alterative sourcing and/or production to deal with limited capacity. Simulation does not have an efficient mechanism for dealing with limited capacity situations. Simulation can certainly identify those situations, but business rules would need to be in place to alleviate those problems and those business rules may not be efficient.

8 WHAT OPTIMIZATION MEANS TO A CORPORATE VICE PRESIDENT

The fact is that senior management could care less about mathematical optimization. In a business sense, to *optimize* is to make something as good as you can *in spite of the variance*. An optimal supply chain delivers product even if the demand forecast is dead wrong. It also operates at an acceptable cost regardless of machine breakdowns, labor shortages and material shortages. To senior management, an optimal supply chain is not mathematically optimal at all. An optimal supply chain is *robust*.

9 REAL APPLICATIONS OF SUPPLY CHAIN SIMULATION

9.1 The Data That Is Needed

The data needed in a supply chain simulation can vary greatly depending on the detail that one wants to simulate. Simulation can model the detail of a manufacturing line or of how one particular truck is loaded. That amount of detail is completely up to the user. However, there is some high level data that is needed regardless of how much detail that the user eventually wants to model. The high level data includes:

1. Demand/Forecast Data – Depending on the modeling environment, you will need either randomly generated demand data or some type of forecasted demand data. This data drives the simulation.
2. Sourcing Data – This data tells the model "where do I get things from."
3. Capacity Data – For each of the manufacturing and inventory sites in the model, there are capacity limits. These limits can be site-wide, or by some key resource. Usually the capacity is either given in units or time.
4. Capacity Consumption Data – At each site, when a product is produced or moved, it consumes some key resources at the site.
5. BOM Data – For manufacturing sites, products that are produced need a bill-of-material to know which raw materials are used.
6. Transportation Data – This data lets the model know how to move product from one site to another. This data can be very complex, including different mode options.
7. Inventory Data – The amount of inventory to be held at different inventory locations in the model.

9.2 Successful Applications

Even though there are many applications of supply chain simulation, below is a list of project that I have been involved with personally where supply chain simulation has shown significant improvements for the supply chain.

1. For the North American market of a given client, we showed increased profitability and significantly increased customer service (over 20% points) by moving certain supplier from Far East to North America.
2. In the Asia/Pacific region of a given client, we showed that high-end products should be produced locally to significantly improve customer service and profitability.
3. For one product group of a given client, we dropped inventory by over 65% and costs by over 20%.

4. For one client, we analyzed the combination of an acquisition to determine the customer satisfaction metrics for the combined customer bases of both companies.

10 CONCLUSION

For those who need to analyze their supply chains, both optimization and simulation both have their place. Simulation shows its strength when the supply chain is very dynamic and has transient performance problems. However, simulating a supply chain can be very complex because a model must mimic several key business processes, including the basic MRP process, planning and scheduling, capital acquisition, labor policies, allocation of constrained resources, etc. However, if a supply chain is modeled correctly, a supply chain simulation can show ways to increase revenues, profitability, and service levels to the customer. This can translate into large financial advantages to the company.

In the introduction, I wrote that I feel like *I am an agent for a great prospect named Supply Chain Simulation and he has some great skills that you need on your team*. Well, I told you *Supply Chain Simulation* has great skills. Are you willing to give him a try?

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