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Multi-Echelon Supply Chain Using Tabu Search Algorithm

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- **Abstract –**

Outsourcing is highly beneficial for any company that values building upon its core competencies, but the emergence of the COVID-19 pandemic and other crises have exposed significant vulnerabilities within supply chains. These disruptions forced a shift in the production of goods from outsourcing to domestic methods. This paper considers a multi-echelon supply chain model with global and domestic raw material suppliers, manufacturing plants, warehouses, and markets. All levels within the supply chain network are evaluated from a holistic perspective, calculating a total cost for all levels with embedded risk. We formulate the problem as a mixed-integer linear model programmed in Excel Solver linear to solve smaller optimization problems. Then, we create a Tabu Search algorithm that solves problems of any size. Excel Solver considers three small-scale supply chain networks of varying sizes, one of which maximizes the decision variables the software can handle. In comparison, the Tabu Search program, programmed in Python, solves an additional ten larger-scaled supply chain networks.

Tabu Search's capabilities illustrate its scalability and replicability. A quadratic multi-regression analysis interprets the input parameters (iterations, neighbors, and tabu list size) association with total supply chain cost and run time. The analysis shows iterations and neighbors to minimize total supply chain cost, while the interaction between iterations x neighbours increases the run time exponentially. Therefore, increasing the number of iterations and neighbours will increase run time but provide a more optimal result for total supply chain cost.

Tabu Search's input parameters should be set high in almost every practical case to achieve the most optimal result. This work is the first to incorporate risk and outsourcing into a multi-echelon supply chain, solved using an exact (Excel Solver) and metaheuristic (Tabu Search) solution methodology.

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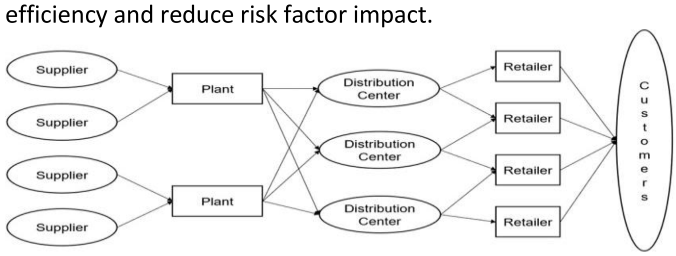
1. INTRODUCTION

- Supply Chain Networks:

A typical multi-echelon supply chain contains levels of suppliers, manufacturers, distributors, retailers, and customers. More specifically, products, information, or funds move between levels over a planning horizon. Modern supply chain network sizes are increasing rapidly due to globalization and the rapid growth of global economies. Companies rely on global supply chain models to meet demand, increase customer value, improve responsiveness, track financials, and establish a quality network. For example, a multi-national company contains different supply chain levels (suppliers, plants, distribution centers, retailers, and customers) worldwide that interconnect into one cohesive system. Supply chain analysts and managers are always looking for ways to reduce costs. Increasing quantity and quality continually increases costs along with embedded risks in the supply chain. Embedded risks tend to hide well in every supply chain, surfacing with great uncertainty. Embedded risks pose numerous problems as they are difficult to pinpoint and quantify to understand their impact on the supply chain. As a result, supply chain management is crucial to increase logistical efficiency and reduce risk factor impact.



2.MATHEMATICAL MODEL FORMULA:

PROBLEM DESCRIPTION

Supply chain risk management has been an increasingly researched topic in the past decade, especially in multi-echelon supply chains. Multi-echelon supply chains drive lower costs, reduce capital assets, and get products to market more efficiently than the competition. They do this by evaluating supply levels and risk probabilities for each possible path between suppliers, plants, warehouses, distributors, and retailers at each level. Rather than a binary matter of receiving the entire supply or not from one source all at once, multi-echelon supply chains assess all supplier avenues and solutions for the final product farthest downstream, which is a better representation of real-life supply chains. Also, many supply chains are incredibly vulnerable to different risk factors that constantly influence operations with the rise of globalization. Costs are often associated with each risk factor when allocating specific goods at the required quality, quantity, place, and time. These issues tie into issues involving outsourcing semi-finished or finished products when in-house production risks are very high. Incorporating this concept into the already established and well-researched topic of multi-echelon supply chain poses a complex challenge that requires solving.

Model Decision Variables:

Notation Description

- $rsDij$ -SDP- Raw material supplied from domestic supplier i to plant j
- $rsOij$- SOP -Raw material supplied from globalsupplier i to plant j
- qij -PW- Quantity supplied from plant i to warehouse j

- qij- WM- Quantity supplied from warehouse i to market j

Objective Function

This model aims to optimize the quantities transferred among all combinations between suppliers-plants, plants-warehouses, and warehouses-markets while minimizing the expected cost of operations with embedded risk. The cost and risk functions considered in this problem are assumed to be known and given based upon historical data found on all suppliers, plants, warehouses, and markets.

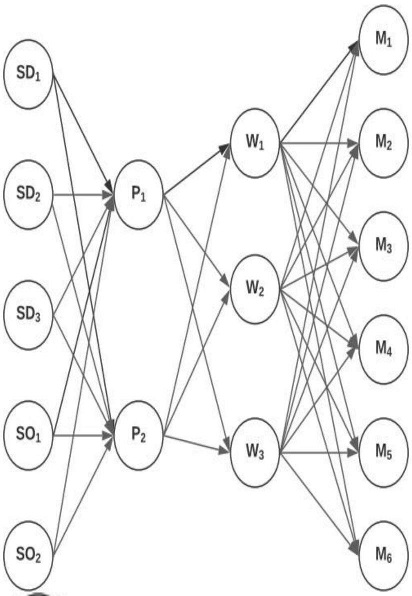
Objective Function Costs

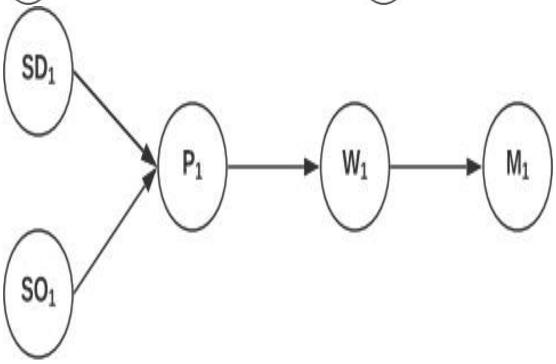
The following sub-costs total up to the supply chain's total cost:

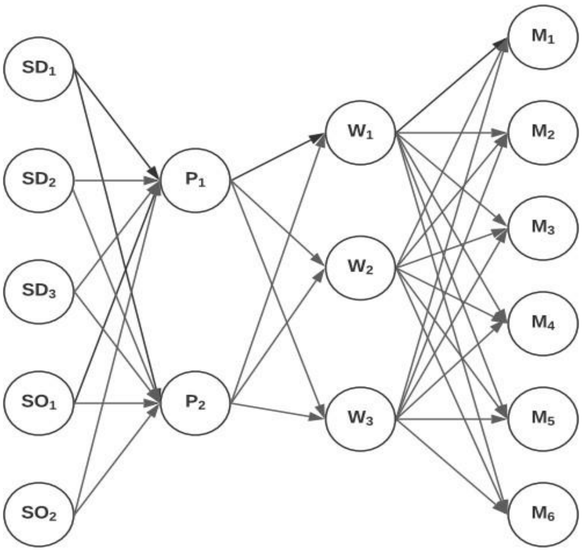
Domestic Supplier Cost
Global Supplier Cost
Plant Production Cost
Plant-Warehouse Cost
Warehouse-Market Cost
Market Cost

$$Min\ TC = DSC + OSC + PC + PWC + WMC + MC$$

SCHEMATIC FOR DIFFERENT SCHEMES:







3. Excel Solver Results

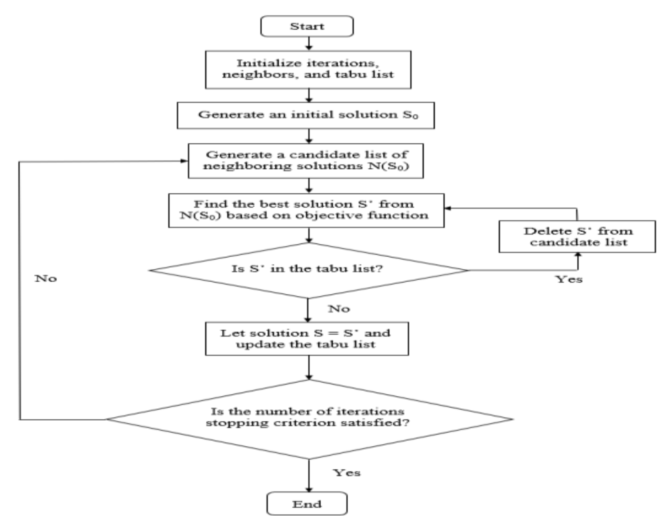
Problem Instance	SD	SO	P	W	M	Total Supply Chain Cost (USD)
1	1	1	1	1	1	$167,707.90
2	3	2	2	3	6	$723,519.52
3	6	6	5	7	15	$1,939,812.60

In all three problem instances, Excel Solver was able to find a global minimum solution for total supply chain cost.. Although we reached an optimal solution with one replication, it is essential to acknowledge Excel Solver's limitations in scalability and replicability. Problem sizes exceeding 200 decision variables prove problematic for the Excel Solver software. Therefore, we present a Tabu Search heuristic in the following chapter.

4.TABU SEARCH HEURISTIC:

The Tabu Search algorithm prevents moves that take the solution into previously visited search spaces known as tabu. While tabu search does accept non-improving solutions, specific parameters prevent the program from getting stuck in local minimums. Tabu Search utilizes short-term memory based on recency of occurrence. Short-term memory returns suitable components to localize and intensify a search known as intensification . It accomplishes this by creating a tabu list. The tabu list is an input parameter to access short-term memory. Tabu list solution moves are kept within the list on a countdown timer as they are not visited more than once.The Tabu Search program contains three key input parameters: iterations number, neighbor size, and tabu list size. Iterations number serves as the stopping criterion and indicates a maximum amount of trial runs. Each provides a total cost preventing the program from being stuck in a continuous loop. The number of neighbors is the number of branches the program chooses to diversify its potential solutions pool. Increasing the number of neighbors increases the total amount of differing solutions. Lastly, the tabu list size parameter stores a limited amount of previously visited solutions and the best solution. Once the tabu list size parameter is full, it ejects older solutions. It brings in newly visited solutions to keep a running list of solutions that the program may not revisit. The program uses a static tabu list.

Tabu Search Flowchart:



Tabu Search Pseudocode:

Algorithm 1: Develop a Solution

1:	**Read in node and edge data.**
2:	**Initialize solution parameters**
3:	**For each market:**
4:	**While market demand ≠ 0, choose random path:**
5:	**If warehouse path already chosen, select new pa**
6:	**If market demand > warehouse capacity, take a**
7:	**Else, satisfy remaining market demands and up**
8:	**For each warehouse:**
9:	**While warehouse demand ≠ 0, choose a random**
10:	**If plant path already chosen, select new path**
11:	**If warehouse demand > plant capacity, take ava**
12:	**Else, satisfy remaining warehouse demands and**
13:	**For each plant:**
14:	**Choose random suppliers and update supplier**
15:	**Calculate single-objective function**
16:	**Return solution**

Algorithm 2: Tabu Search

1:	**Initialize Tabu Search parameters: iterations, n**
2:	**Generate initial solution S_0**
3:	**Run Tabu Search algorithm**
4:	**While iterations ≤ stopping criterion:**
5:	**Generate neighborhood of solutions $N(S_0)$**
6:	**Select best, unique solution (S') and add to tabu**
7:	**Update tabu list with most recent solutions and**
8:	**Return current best solution**

From the Tabu Search Data Parameters the tabu instances and results are tabulated.

5.STATISTICAL ANALYSIS:

Regression Analysis of Total Supply Chain Cost:

A quadratic multi-regression approach describes the relationship between the input parameters (iterations, neighbors' number, and tabu list size) and the response (total supply chain cost ($)). The input parameters act as independent continuous predictors, while the response serves as a continuous dependent variable. Equation 29 describes the regression equation with both linear, quadratic, and interaction terms.

$$(Y) = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 11X1\ 2 + \beta 22X2\ 2 + \beta 33X3\ 2 + \beta 12X1X2 + \beta 13X1X3 + \beta 23X2X3 + \beta 123X1X2X3$$

Quadratic Multi-Regression:

First, we conduct a multi-regression analysis with quadratic and linear interaction terms shown in Table 5-1. Then, we analyze if the regression model is significant. We use Minitab version 19 to conduct the regression analysis with a significance level (denoted as α) of 0.05. The regression's p-value is less than 5%, meaning we have a significant regression model. In addition, we test for the significance of the model's constant. The model constant's p-value is less than 5%, meaning we have a non-zero constant intercept.

Total Supply Chain Cost Regression Analysis:

Regression Equation Total Supply Chain Cost ($) = 2924406 - 1540 Iterations - 422 Neighbors - 386 Tabu List Size + 1.865 Iterations*Iterations + 0.151 Neighbors*Neighbors - 0.39 Tabu List Size*Tabu List Size - 0.058 Iterations*Neighbors + 1.79 Iterations*Tabu List Size - 0.29 Neighbors*Tabu List Size + 0.00145 Iterations*Neighbors*Tabu List Size

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2924406	91301	32.03	0.000	
Iterations	-1540	452	-3.40	0.001	68.25
Neighbors	-422	302	-1.40	0.163	68.25
Tabu List Size	-386	905	-0.43	0.670	68.25
Iterations*Iterations	1.865	0.738	2.53	0.012	49.00
Neighbors*Neighbors	0.151	0.328	0.46	0.646	49.00
Tabu List Size*Tabu List Size	-0.39	2.95	-0.13	0.895	49.00
Iterations*Neighbors	-0.058	0.621	-0.09	0.926	36.00
Iterations*Tabu List Size	1.79	1.86	0.96	0.338	36.00
Neighbors*Tabu List Size	-0.29	1.24	-0.24	0.814	36.00
Iterations*Neighbors*Tabu List Size	0.00145	0.00469	0.31	0.758	48.25

Model Summary

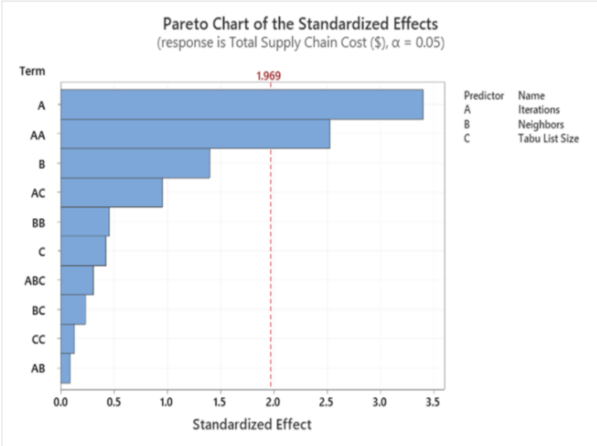
S	R-sq	R-sq(adj)	R-sq(pred)
112250	32.54%	29.93%	27.21%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	1.57404E+12	1.57404E+11	12.49	0.000
Iterations	1	1.45919E+11	1.45919E+11	11.58	0.001
Neighbors	1	24687330199	24687330199	1.96	0.163
Tabu List Size	1	2290034582	2290034582	0.18	0.670
Iterations*Iterations	1	80481369454	80481369454	6.39	0.012
Neighbors*Neighbors	1	2659595076	2659595076	0.21	0.646
Tabu List Size*Tabu List Size	1	221015477	221015477	0.02	0.895
Iterations*Neighbors	1	108465129	108465129	0.01	0.926
Iterations*Tabu List Size	1	11588120667	11588120667	0.92	0.338
Neighbors*Tabu List Size	1	696023913	696023913	0.06	0.814
Iterations*Neighbors*Tabu List Size	1	1202252366	1202252366	0.10	0.758
Error	259	3.26340E+12	12599997398		
Lack-of-Fit	16	2.20485E+11	13780288705	1.10	0.355
Pure Error	243	3.04291E+12	12522282744		
Total	269	4.83744E+12			

Predictor Association:

Total Supply Chain Cost Pareto Chart for Significant Predictors:



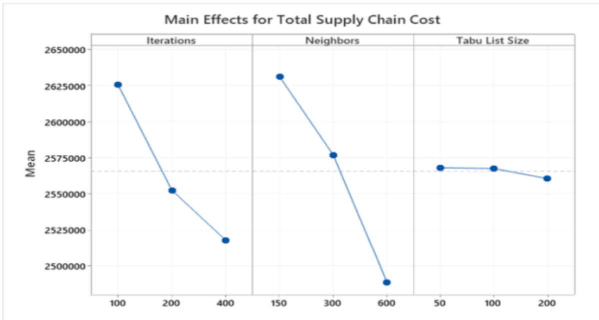


Figure 5-2: Run Time Main Effects Plot

CONCLUSION:

This paper successfully created a multi-echelon supply chain network using domestic and globalsuppliers with embedded risk cost functions. A mixed-integer linear model illustrates these networks. First, the mathematical model was programmed and solved in Excel Solver for three smaller problems.

Then, we modeled the problem with a Tabu Search algorithm for larger problem instances. While exact methods like Excel Solver can solve problems to optimality, they struggle with scaled problems. Given data for nodes and edges, the Tabu Search algorithm can solve any size problems and does a great job finding a quality solution amongst a large pool of possible solutions within a relatively short time.

The primary motivation behind this research is the rise of the COVID-19 pandemic. COVID-19 impacted every supply chain around the world. Although the virus slowed or shut down supply chains worldwide, it was highly beneficial for companies to view their supply chains differently. Overall, the pandemic accentuated the existing issues within supply chains and increased efforts in risk management to reduce costs.

The purpose of using a commercial solver and Tabu Search was not to compare the two results of similar problem instances. Instead, the objective was to illustrate that a commercial solver like Excel Solver is incapable of solving large-scale 76 supply chain optimization problems. Thus, Tabu Search is a viable alternative to good results with a relatively fast run time, illustrating scalability and replicability.

FUTURE SCOPE:

Only suppliers (domestic and global), plants, warehouses, and markets make up the supply chain network in this paper. It would be interesting also to consider other supply chain states such as retailers, distribution centers, or manufacturers.

100% of materials/goods transfer to the next echelon in the supply chain network in the studied problems. It would be interesting to account for quality,specifically 81 incorporating scrapped or missing transit parts to simulate real-world logistical issues.

The model in this paper identifies supply chain network paths based on the cost it incurs to take such a path. It would be interesting to assume that the cost for multiple routes is equal, and some other deciding factor must be considered, such as loyalty, convenience, or locality of products.

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