SUPPLY NETWORK OPTIMIZATION FOR CHICAGO TOOLS

Identifying cost savings opportunities using optimization techniques.

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Executive Summary

Background and Objective

Chicago Tools, an Engineering equipment company headquartered at Bridgeview, Illinois is looking to evaluate their current supply chain design and explore any cost saving opportunities. They currently manufacture products in two locations in the US with a customer base solely in Canada for the business unit in scope.

The Director of Distributions at Chicago Tools has engaged us, AAA consultants to provide solution to their business problem and has provided last one year's shipment details (both inbound i.e. from manufacturing plants to warehouses and outbound i.e. warehouses to customers in Canada) and cost data files for analysis. These data files had details like zip code, items that were shipped, weight(lbs) of items being shipped, distance(mi) between origin and destination, freight charge (USD) and others.

The two objectives as specified by the client were:

1. Identify any untapped cost savings opportunities if the supply chain nodes remain the same.
2. Identify the optimal number of warehouses that offers the most cost savings.

To be able to come up with a solution to the business problem, we designed an optimization model and recommended ways to minimize the overall supply chain cost. We also provided Chicago Tools with a handy tool to experiment with the number of warehouses that they would want to keep active and accordingly decide on the best implementation steps for their organization.

There were certain assumptions that we considered while building an optimization model which are listed in the appropriate sections.

If Chicago Tools were to provide additional data with respect to changing customer patterns, acquisition/consolidation plans, we could incorporate this into the existing model to refine our recommendations.

Introduction

Chicago Tools have manufacturing facilities in the United States of America while the customers are in Canada. Every month they manufacture and ship connectors from their two plants in the US to four warehouses situated across the border. These warehouses then fulfil the demand for ten different customers spread across Canada. A quick glance at the historical data showed coast-to-coast shipments, both inbound into the warehouses and outbound from the warehouses. For example, the plant in Sacramento, CA shipped connectors to a warehouse in Moncton, NB at a distance of 3,493 miles when it could have come from the other geographically closer plant in Litchfield, IL. There are a lot of similar scenarios which we observed. This shows that there could be potential opportunities to optimize the flow. We will discuss this in detail in the data analysis section. Specifically we will address the following:

1. Optimize the existing baseline to identify untapped cost saving opportunities in both inbound and outbound shipments.
2. Evaluate the possibility of reducing the number of active warehouses.
3. Evaluate the possibility of increasing capacity of manufacturing plants.

Main Chapter

Data Collection and Preparation:

Data provided by Chicago Tools had details of shipments for both inbound and outbound flows:

Inbound flow: From two manufacturing plants in the USA to four warehouses in Canada.

Plants: Litchfield, IL and Sacramento, CA

Warehouses: Calgary, AB; Markham, ON; Moncton, NB; Coquitlam, BC

PO #	Origin City	Origin State	Origin Zip	Destination City	Destination State	Destination Zip	Item Description	Total Weight (lbs.)	Distance (mi)	Freight Charge (USD)
3160	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30873.525	733	2272.29144
3162	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30805.725	733	2267.30136
3163	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30755.125	733	2263.5772
3164	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	31214.525	733	2297.38904
3169	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30798.125	733	2266.742
3170	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	31126.125	733	2290.8828
3171	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30064.525	733	2212.74904
3174	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	29959.525	733	2205.02104
3175	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30955.325	733	2278.31192
3182	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30479.525	733	2243.29304
3183	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30963.325	733	2278.90072
3184	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	29659.325	733	2182.92632
3193	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30572.725	733	2250.15256
3194	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30410.525	733	2238.21464
3195	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30499.925	733	2244.79448
3200	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	29951.325	733	2204.41752
3205	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30256.525	733	2226.88024
3206	Litchfield	IL	62056	Markham	ON	L3R5B3	Connectors	30761.725	733	2264.06296

Figure 1- A snapshot of the data provided by Chicago tools

Outbound flow: From four warehouses to ten customers all situated in Canada.

Customers: Ten customers are based out of - Calgary, AB; Charlottetown, PE; Clavet, SK; Coquitlam, BC; Halifax, NS; Markham, ON; Moncton, NB; Montreal, QC; St Johns, NL; Winnipeg, MB

PO #	Origin City	Origin State	Origin Zip	Destination City	Destination State	Destination Zip	Item Description	Total Weight (lbs.)	Distance (mi)	Freight Charge (USD)
7283	Moncton	NB	E1E3Y9	Moncton	NB	E5T1X3	Connectors	3872	9	6.9696
7328	Moncton	NB	E1E3Y9	Moncton	NB	E5T1X3	Connectors	3670	9	6.606
7200	Moncton	NB	E1E3Y9	St Johns	NL	A0A1T0	Connectors	7471	965	1441.903
6231	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	828	162	26.8272
6358	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	516	162	16.7184
6372	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	3260	162	105.624
6414	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	3475	162	112.59
6462	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	406	162	13.1544
6471	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	11254	162	364.6296
6507	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	1537	162	49.7988
6526	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	3895	162	126.198
6547	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	508	162	16.4592
6595	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	29139	162	944.1036
6634	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	585	162	18.954
6805	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	2733	162	88.5492
6905	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	3391	162	109.8684
6934	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	1012	162	32.7888
7038	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	128	162	4.1472
7076	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	194	162	6.2856
7134	Moncton	NB	E1E3Y9	Halifax	NS	B0S1P0	Connectors	248	162	8.0352

Figure 2- Data provided by Chicago Tools(contd.)

For the plants,warehouses,customers we have details such as city, state and zip code.

For every origin-destination pair (both inbound and outbound) we have information on shipment weights(lbs), distance(miles) and the freight charge($) incurred. We were also told that each warehouse has an operating cost of $200,000 for the period in consideration. Additionally, we were asked to use a normalized rate of $0.0001/mile/lb. for the inbound shipments and $0.0002/mile/lb. for the outbound leg for modelling purposes.

Since network modelling exercises do not call for detailed shipment level data by date the team decided to aggregate the shipments for the period by origin-destination level.

Inbound Baseline

Distance (mi)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	1760	2319	733	1648
Sacramento	1241	887	2557	3493

Weight (lbs.)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	863985	0	3550601	383000
Sacramento	0	523508	0	382373

Rate ($/mi/lb.)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	0.0001	0.0001	0.0001	0.0001
Sacramento	0.0001	0.0001	0.0001	0.0001

Inbound baseline spending	$655,436.86	
Warehouse operating cost	$800,000.00	Each warehouse costs $200,000 per period to operate.

Figure 3-Inbound baseline costs

Outbound Baseline

Distance (mi)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	12	2895	389	591	3002	2016	2794	2188	3757	828
Coquitlam	592	3526	973	16	3585	2608	3425	2819	4388	1416
Markham	2016	1047	1683	2586	1107	19	946	330	1910	1269
Moncton	2791	102	2479	3422	162	946	9	608	965	2009

Weight (lbs)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	839918	0	7499	16568	0	0	0	0	0	0
Coquitlam	53259	0	0	470249	0	0	0	0	0	0
Markham	7081	0	191792	0	334547	1298475	0	988682	206097	523927
Moncton	0	39120	0	0	265081	42210	386168	10148	22646	0

Rate ($/mi/lb.)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Coquitlam	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Markham	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Moncton	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002

Outbound baseline	$459,410.70			
Total cost (Inbound+Outbound+ Warehouse operational cost for 4 warehouses)	**$1,914,847.56**	Total actual cost incurred	$ 1,909,547.39	
		Baseline deviation from actual cost incurred		0.28%

Figure 4 - Out bound baseline, total costs and actual cost

Data Analysis

Based on the historical flow, transportation rate and the warehouse operating cost ,the baseline model cost is $1.91 MM. This is within 0.3% of the actual cost incurred by Chicago tools for the period in scope. This shows that the rates used in the model are reasonably accurate.

The geographical map below helps us understand the different shipment paths for Chicago Tools both inbound and outbound. We have two plants i.e. Sacramento and Litchfield which supply items to four warehouses and they further ship items to ten customers. All paths have been depicted in the map below. On a cursory look one can assume that Sacramento which is on the west coast of the US can replenish inventory of warehouses and customers which are on the west coast of Canada like Coquitlam, Calgary and Clavet. Similarly, Litchfield which is towards the east coast can supply Markham and Moncton warehouses which can further handle orders from customers on the same side like St. Johns, Halifax etc. However, with Chicago Tools this is not the case because the Sacramento plant is shipping to Moncton (the purple path on the map originating at Sacramento ending at Moncton) which is on the opposite side of the map which should ideally be handled by Litchfield plant. Similarly, Litchfield is shipping to Calgary(the blue path line originating at Litchfield and ending at Calgary-WH in the map) which is closer to Sacramento than Litchfield. Hence, we observed non-efficient shipment routes which could be a mistake or could be because of other factors at play (i.e. plant manufacturing capacity). We plan to address such issues with our optimization model.

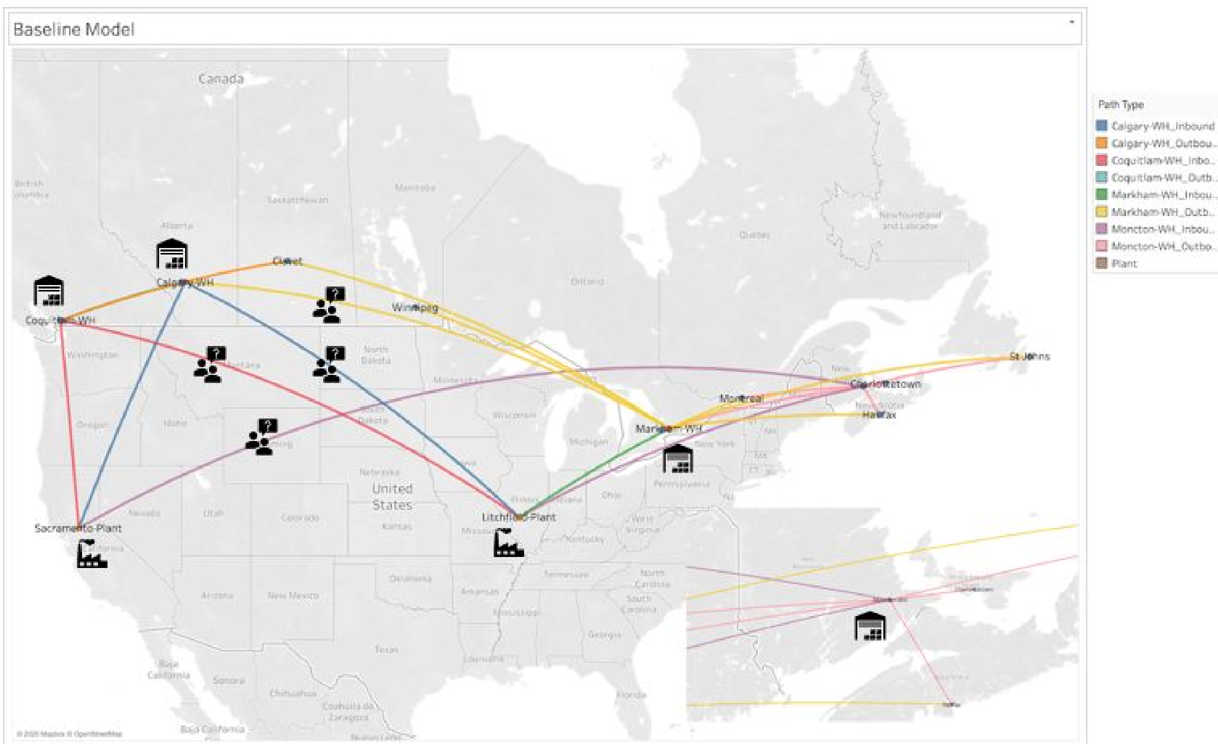


*Figure 5 - Visual idea of the baseline flow of Chicago Tools ***

*** Differently colored lanes show inbound and outbound flows. Locations with showcase plants, showcase warehouses and rest are all customers. depicts non-efficient shipment routes which are to be analyzed.*

In order to understand the cost saving potential, we analyzed the data to conclude that cost is majorly driven by the distance between origin and destination and the weight being shipped, as rate ($/mi/lb.) of shipment is constant across all routes owing to a negotiated company deal with the transport service provider. So, to provide a solution to Chicago Tools' business problem, we need to be able to optimize right weight being shipped in the lanes.

Data Modeling

Baseline Model

Baseline model was formulated using the historical data (both inbound and outbound) we had, and it maps the historical flow quantities between origin and destination nodes as it is in the current scenario. This is to establish what the current cost is to serve the customers.

<u>Few assumptions we considered while calculating the optimized baseline:</u>

1. Carrier costs remain the same.
2. Customer locations remain the same as provided by Chicago Tools.
3. As per our data, this division of Chicago Tools exports their products to customers in Canada. The total transportation cost includes any charges associated with international shipments.
4. All costs are in US Dollars.

We identified Inbound baseline spend as $ 655,436.86 and outbound shipment cost as $ 459,410.70. This shows that Chicago Tools spends more on inbound shipments which involve shipment from 2 manufacturing plants to 4 warehouses. This justifies our finding of shipment to far away destinations like from Sacramento to Moncton. There is a scope to reduce this cost by some value. The total baseline cost is $1.91 MM and it includes $800,000 in warehouse operating cost ($200,000 each for the four warehouses).

Optimized Model

Having completed our data retrieval, data preparation and discussions with stakeholders, we were ready to optimize the model. We developed a Multi-Integer optimization model where we had 52 decision variables, one objective function, inputs like Distance and shipment rate. Also, we defined constraints to the inputs and decision variables as considered relevant by Chicago Tools. Below is the explanation for the same:

p	index for plants of Chicago Tools (p = L, S) *L= Litchfield; S = Sacramento*
w	index for warehouses (w = 1,2,3,4) *1 = Calgary; 2 = Coquitlam; 3 = Markham; 4 =Moncton*
c	index for Customers (c = 0 to 9) 0 = Calgary; 1 = Charlottetown; 2 = Clavet; 3= Coquitlam; 4 = Halifax; 5 = Markham; 6 = Moncton; 7 = Montreal; 8 = St Johns; 9 = Winnipeg
X	Weights being shipped from origin to destination
C_w	Cost of operating warehouse
D_{pw}	Distance between plant and warehouses
D_{wc}	Distance between warehouse and customers
R_{pw}	Rate ($/mi/lb.) of shipment between plant and warehouses
R_{wc}	Rate ($/mi/lb.) of shipment between warehouses and customers

Table 1- constraints to the inputs and decision variables

As ***inputs***, we were given Distance and rate of shipment to warehouses and customers:

Distance and Rate of shipment from plants to warehouse:

Inbound

Distance(miles)	**Warehouses**			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	1760	2319	733	1648
Sacramento	1241	887	2557	3493

Rate ($/mi/lb.)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	$ 0.0001	$ 0.0001	$ 0.0001	$ 0.0001
Sacramento	$ 0.0001	$ 0.0001	$ 0.0001	$ 0.0001

Figure 6 - Distance and Shipment - Inbound

<u>Distance and Rate of shipment from warehouse to customers:</u>

Outbound

Distance(miles)	**Customers**									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	12	2895	389	591	3002	2016	2794	2188	3757	828
Coquitlam	592	3526	973	16	3585	2608	3425	2819	4388	1416
Markham	2016	1047	1683	2586	1107	19	946	330	1910	1269
Moncton	2791	102	2479	3422	162	946	9	608	965	2009

Rate ($/mi/lb.)	**Customers**									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Coquitlam	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Markham	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Moncton	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002

Figure 7 - Distance and shipment rates - Outbound

Decision variables:

X_{pw}	*Weights being shipped from plant to warehouse (where p = L, S and w = 1,2,3,4)*
X_{wc}	*Weights being shipped from plant to warehouse (where w = 1 to 4 and c = 0 to 9)*
W_w	*Binary variable (0-1) showcasing Warehouse being close or open (where w = 1 to 4)*

X_{pw} :

Weight (lbs.)	**Warehouses**			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	X_{L1}	X_{L2}	X_{L3}	X_{L4}
Sacramento	X_{S1}	X_{S2}	X_{S3}	X_{S4}

X_{wc} :

Weight (lbs.)	Customers									
Warehouses	Calgary	Charlottetow	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}
Coquitlam	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}
Markham	X_{30}	X_{31}	X_{32}	X_{33}	X_{34}	X_{35}	X_{36}	X_{37}	X_{38}	X_{39}
Moncton	X_{40}	X_{41}	X_{42}	X_{43}	X_{44}	X_{45}	X_{46}	X_{47}	X_{48}	X_{49}

W_w:

Warehouse	Calgary	Coquitlam	Markham	Moncton
Open/close	W_1	W_2	W_3	W_4

Objective function:

Minimize total shipment cost i.e. minimize both Inbound shipment cost and outbound shipment cost which is a function of Distance between origin and destination along with weight and rate of shipment. It also includes warehouse operational cost which is dependent on the number of functional/open warehouses.

$$\textbf{Min } \underbrace{C_w * \sum_{w=1}^{4} W_w}_{\textit{Warehouse operational cost}} + \underbrace{\sum_{p=L}^{S} \sum_{w=1}^{4} (D_{pw} * X_{pw} * R_{pw})}_{\textit{Inbound shipment cost}} + \underbrace{\sum_{w=1}^{4} \sum_{c=0}^{9} (D_{wc} * X_{wc} * R_{wc})}_{\textit{Outbound shipment cost}}$$

Constraints:

We sat down with the Supply Chain Director and her managers to understand the constraints they may have regarding manufacturing capacity or shipment load. We also wanted to understand if there are specific demands for items by different customers to assess how much of it can be handled by a specific manufacturing plant. Also, we wanted to be sure if warehouses can hold surplus inventory or they run on zero storage. Based on our discussion, below are the constraints that are part of the supply chain for Chicago Tools:

Supply constraints:

Maximum production capacity of Litchfield Plant: $\sum_{w=1}^{4} X_{LW} \leq 4{,}900{,}000$

Maximum production capacity of Sacramento Plant: $\sum_{w=1}^{4} X_{SW} \leq 2{,}000{,}000$

Demand constraints:

Minimum requirement for Calgary Customer: $\sum_{w=1}^{4} X_{w0} \geq 900{,}258$

Minimum requirement for Charlottetown Customer: $\sum_{w=1}^{4} X_{W1} \geq 39{,}120$

Minimum requirement for Clavet Customer: $\sum_{w=1}^{4} X_{w2} \geq 199{,}291$

Minimum requirement for Coquitlam Customer: $\sum_{w=1}^{4} X_{w3} \geq 486{,}817$

Minimum requirement for Halifax Customer: $\sum_{w=1}^{4} X_{w4} \geq 599{,}628$

Minimum requirement for Markham Customer: $\sum_{w=1}^{4} X_{w5} \geq 1{,}340{,}685$

Minimum requirement for Moncton Customer: $\sum_{w=1}^{4} X_{w6} \geq 386{,}168$

Minimum requirement for Montreal Customer: $\sum_{w=1}^{4} X_{w7} \geq 998{,}830$

Minimum requirement for St Johns Customer: $\sum_{w=1}^{4} X_{w8} \geq 228{,}743$

Minimum requirement for Winnipeg Customer: $\sum_{w=1}^{4} X_{w9} \geq 523{,}927$

Conservation of flow constraints:

What flows into the warehouse should flow out of the warehouse -

Shipment sent to Calgary warehouse: $\sum_{p=L}^{S} X_{p1} = \sum_{c=0}^{9} X_{1C}$

Shipment sent to Coquitlam warehouse: $\sum_{p=L}^{S} X_{p2} = \sum_{c=0}^{9} X_{2C}$

Shipment sent to Markham warehouse: $\sum_{p=L}^{S} X_{p3} = \sum_{c=0}^{9} X_{3c}$

Shipment sent to Moncton warehouse: $\sum_{p=L}^{S} X_{p4} = \sum_{c=0}^{9} X_{4c}$

Linking constraints:

This constraint ensures that the warehouse is open/functional if any quantity flows through it.

Similarly, it is closed if no quantity flows through it.

Equation used to enforce this constraint:

Linking constraint = Weight flowing through a warehouse - (open/close binary warehouse variable * Big M number)

Where the big M number is the total demand (sum of historical demands in our case).

Total Demand (TD) = $\sum_{c=0}^{9} X_{1c} + \sum_{c=0}^{9} X_{2c} + \sum_{c=0}^{9} X_{3c} + \sum_{c=0}^{9} X_{4c}$

Linking Constraint for warehouse 1: $\sum_{c=0}^{9} X_{1c}$ - (W_1*TD) ≤ 0

Linking Constraint for warehouse 2: $\sum_{c=0}^{9} X_{2c}$ - (W_2*TD) ≤ 0

Linking Constraint for warehouse 3: $\sum_{c=0}^{9} X_{3c}$ - (W_3*TD) ≤ 0

Linking Constraint for warehouse 4: $\sum_{c=0}^{9} X_{4c}$ - (W_4*TD) ≤ 0

Post completion of model formulation, we set out to solve the model and derive actionable recommendations for Chicago Tools.

Solution results & analysis

We have 52 decision variables out of which 4 are binary variables and rest are non-negative variables. Hence, we decided to design a Multi-Integer optimization model using Simplex LP method. We used Microsoft Excel Solver Add-In and SolverTable Add-in to build a model and do further analysis. Below is the solution for the optimized baseline (keeping all four warehouses open) and the optimized model (letting the model decide the optimal number of warehouses) that we derived from the model, refer to the legend key below to understand the model and different components:

Optimized Baseline Model with four functional warehouses:

The optimized baseline model retains the same number of warehouses and the same production levels at the manufacturing plants to determine the best possible ways to route the connectors from their place of origin to the demand locations. In the spreadsheet - LP model this is achieved by fixing the number of warehouses to 4.

Legends:

	Obj. function
	Constraints
	Decision variables

Input and decision variables for Inbound shipment:

Inbound

Distance(miles)	Warehouses			
Row Labels	Calgary	Coquitlam	Markham	Moncton
Litchfield	1760	2319	733	1648
Sacramento	1241	887	2557	3493

Weight (lbs.)	Warehouses			
Row Labels	Calgary	Coquitlam	Markham	Moncton
Litchfield	0	0	2449808	1253659
Sacramento	1513183	486817	0	0

Rate ($/mi/lb.)	Warehouses			
Row Labels	Calgary	Coquitlam	Markham	Moncton
Litchfield	$ 0.0001	$ 0.0001	$ 0.0001	$ 0.0001
Sacramento	$ 0.0001	$ 0.0001	$ 0.0001	$ 0.0001

Warehouse	Calgary	Coquitlam	Markham	Moncton
Open/close	1	1	1	1

Total warehouses open =	4
No. of WH that must be open	4

Figure 8 - Inbound model input and output with 4 functional warehouses

Input and decision variables for Outbound shipment:

Outbound

Distance(miles)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	12	2895	389	591	3002	2016	2794	2188	3757	828
Coquitlam	592	3526	973	16	3585	2608	3425	2819	4388	1416
Markham	2016	1047	1683	2586	1107	19	946	330	1910	1269
Moncton	2791	102	2479	3422	162	946	9	608	965	2009

Weight (lbs.)	Customers											Linking constraint		
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg	Total			
Calgary	900258	0	199291	0	0	0	0	0	0	413634	1513183	-4190284	<=	0
Coquitlam	0	0	0	486817	0	0	0	0	0	0	486817	-5216650	<=	0
Markham	0	0	0	0	0	1340685	0	998830	0	110293	2449808	-3253659	<=	0
Moncton	0	39120	0	0	599628	0	386168	0	228743	0	1253659	-4449808	<=	0
										Total demand =	5,703,467.00			

Rate ($/mi/lb.)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Coquitlam	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Markham	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Moncton	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002

Figure 9 - Outbound model input and output with 4 functional warehouses

Constraints for both Inbound and outbound shipments:

Constraints:	L.H.S		R.H.S	
Supply constraints:				
Maximum production capacity of Litchfied Plant	3,703,467	<=	4,900,000.00	
Maximum production capacity of Sacramento Plant	2,000,000	<=	2,000,000.00	
Demand constraints:				
Minimum requirement for Calgary Customer	900,258	>=	900,258.00	(historical demand from baseline)
Minimum requirement for Charlottetown Customer	39,120	>=	39,120.00	(historical demand from baseline)
Minimum requirement for Clavet Customer	199,291	>=	199,291.00	(historical demand from baseline)
Minimum requirement for Coquitlam Customer	486,817	>=	486,817.00	(historical demand from baseline)
Minimum requirement for Halifax Customer	599,628	>=	599,628.00	(historical demand from baseline)
Minimum requirement for Markham Customer	1,340,685	>=	1,340,685.00	(historical demand from baseline)
Minimum requirement for Moncton Customer	386,168	>=	386,168.00	(historical demand from baseline)
Minimum requirement for Montreal Customer	998,830	>=	998,830.00	(historical demand from baseline)
Minimum requirement for St Johns Customer	228,743	>=	228,743.00	(historical demand from baseline)
Minimum requirement for Winnipeg Customer	523,927	>=	523,927.00	(historical demand from baseline)
Conservtion of flow constraint:				
What flows into the warehouse should flow out of the warehouse				
Shipment sent to Calgary warehouse	1,513,183	=	1,513,183	Shipment sent out of Calgary warehouse
Shipment sent to Coquitlam warehouse	486,817	=	486,817	Shipment sent out of Coquitlam warehouse
Shipment sent to Markham warehouse	2,449,808	=	2,449,808	Shipment sent out of Markham warehouse
Shipment sent to Moncton warehouse	1,253,659	=	1,253,659	Shipment sent out of Moncton warehouse

Linking constraints

This constraint ensures that the warehouse is opened if any quantity flows through it

Equation used to enforce this constraint:

Linking constraint = Weight flowing through a warehouse - (open/close binary variable * Big M number)

Where the big M number is the total demand (sum of historial demands in our case)

Figure 10 - Model constraints

Objective function (Optimal minimum total shipment cost to Chicago Tools):

Cost of doing business

Total warehouse cost	$ 800,000.00
Total inbound cost	$ 617,140.61
Total outbound cost	$ 251,799.31
Total Cost	**$ 1,668,939.91**
(Objective function)	

Figure 11 - Model output for objective function (4 operational warehouses)

Recommendations from the Optimized Baseline model with 4 operational warehouses:

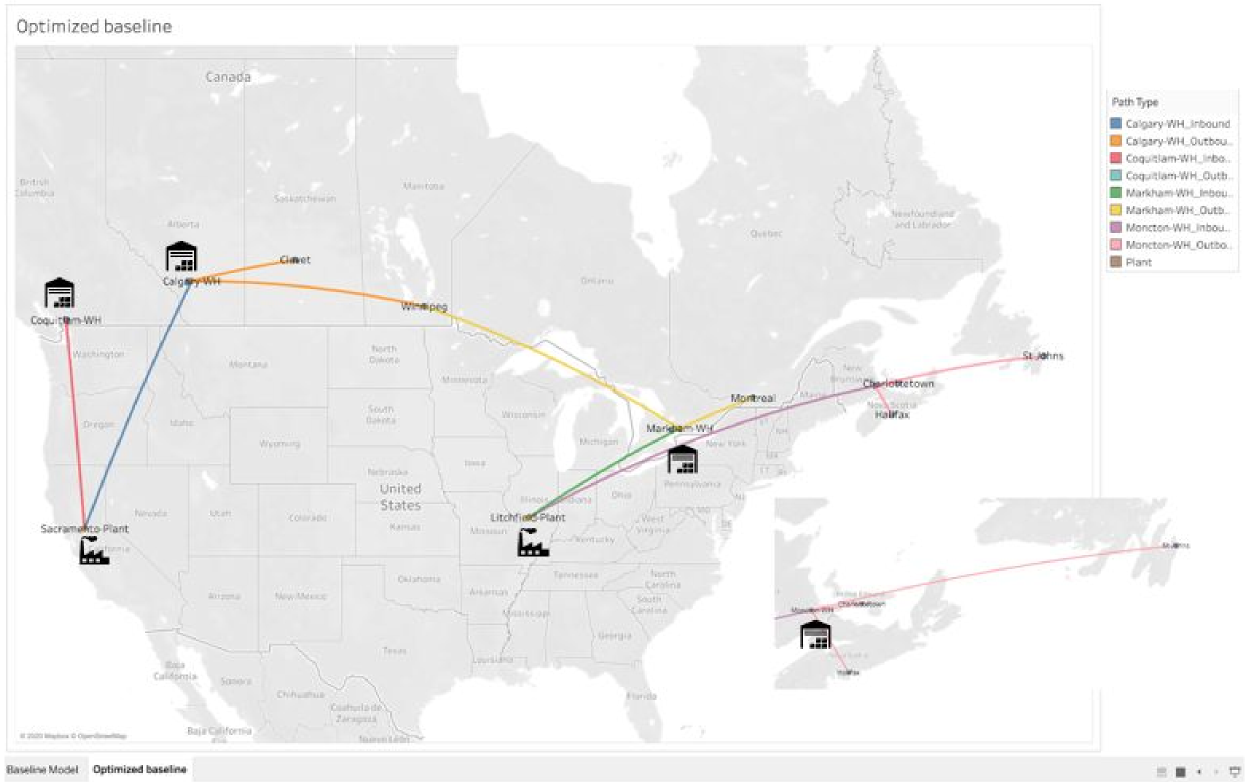


Figure 12 - Visual idea of the optimized baseline flow for Chicago Tools

The optimized baseline model comes up with an overall cost of $1.67 MM which includes the $800,000 of warehouse operating cost leading to a cost savings opportunity of $240,000. This represents the money left behind on the table that Chicago Tools could recover by just optimizing the inbound and outbound flows. As shown in figure-12 as we had suspected earlier these additional costs were coming from poor planned routes running from one coast to the other. Our recommendation to Chicago Tools from this optimized baseline mode is that even if they continue to operate the same four warehouses ,the same two plants with the same capacity and the same transportation rates, they would be able to save roughly $240,000 just by planning the routes properly.

Optimized Model with two operational warehouses:

Legends:

	Obj. function
	Constraints
	Decision variables

Input and decision variables for Inbound shipment:

Inbound

Distance(miles)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	1760	2319	733	1648
Sacramento	1241	887	2557	3493

Weight (lbs.)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	0	0	3703467	0
Sacramento	2000000	0	0	0

Rate ($/mi/lb.)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	$ 0.0001	$ 0.0001	$ 0.0001	$ 0.0001
Sacramento	$ 0.0001	$ 0.0001	$ 0.0001	$ 0.0001

Warehouse	Calgary	Coquitlam	Markham	Moncton
Open/close	1	0	1	0

Total warehouses open =	2
(no constraints on the no. of WHs to be kept open)	

Figure 13 - Inbound Model input and output for objective function (with 2 operational warehouses)

Input and decision variables for Outbound shipment:

Outbound

Distance(miles)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	12	2895	389	591	3002	2016	2794	2188	3757	828
Coquitlam	592	3526	973	16	3585	2608	3425	2819	4388	1416
Markham	2016	1047	1683	2586	1107	19	946	330	1910	1269
Moncton	2791	102	2479	3422	162	946	9	608	965	2009

Weight (lbs.)	Customers													
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg	Total	Linking constraint		
Calgary	900258	0	199291	486817	0	0	0	0	0	413634	2000000	(3,703,467.00)	<=	0
Coquitlam	0	0	0	0	0	0	0	0	0	0	0	0	<=	0
Markham	0	39120	0	0	599628	1340685	386168	998830	228743	110293	3703467	-2000000	<=	0
Moncton	0	0	0	0	0	0	0	0	0	0	0	0	<=	0
										Total demand =	5,703,467.00			

Rate ($/mi/lb.)	Customers									
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg
Calgary	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Coquitlam	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Markham	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002
Moncton	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002	$ 0.0002

Figure 14 - Outbound Model input and output for objective function (with 2 operational warehouses)

Constraints for both Inbound and outbound shipments:

Note that all constraints are binding except for Litchfield plant's production capacity. This plant has surplus capacity and possibly can supply any impromptu demand from existing customers or any new customers in future.

Constraints:	L.H.S		R.H.S	
Supply constraints:				
Maximum production capacity of Litchfied Plar	3703467	<=	4,900,000.00	
Maximum production capacity of Sacramento	2000000	<=	2,000,000.00	
Demand constraints:				
Minimum requirement for Calgary Customer	900258	>=	900,258.00	(historical demand from baseline)
Minimum requirement for Charlottetown Cust	39120	>=	39,120.00	(historical demand from baseline)
Minimum requirement for Clavet Customer	199291	>=	199,291.00	(historical demand from baseline)
Minimum requirement for Coquitlam Custome	486817	>=	486,817.00	(historical demand from baseline)
Minimum requirement for Halifax Customer	599628	>=	599,628.00	(historical demand from baseline)
Minimum requirement for Markham Custome	1340685	>=	1,340,685.00	(historical demand from baseline)
Minimum requirement for Moncton Customer	386168	>=	386,168.00	(historical demand from baseline)
Minimum requirement for Montreal Customer	998830	>=	998,830.00	(historical demand from baseline)
Minimum requirement for St Johns Customer	228743	>=	228,743.00	(historical demand from baseline)
Minimum requirement for Winnipeg Customer	523927	>=	523,927.00	(historical demand from baseline)
Conservation of flow constraint:				
What flows into the warehouse should flow out of the warehouse				
Shipment sent to Calgary warehouse	2000000	=	2000000	Shipment sent out of Calgary warehouse
Shipment sent to Coquitlam warehouse	0	=	0	Shipment sent out of Coquitlam warehouse
Shipment sent to Markham warehouse	3703467	=	3703467	Shipment sent out of Markham warehouse
Shipment sent to Moncton warehouse	0	=	0	Shipment sent out of Moncton warehouse

Linking constraints

This constraint ensures that the warehouse is opened if any quantity flows through it

Equation used to enforce this constraint:

Linking constraint Weight flowing through a warehouse - (open/close binary variable * Big M number)

Where the big M number is the total demand (sum of historial demands in our case)

Figure 15 - Model constraints

Objective function (Optimal minimum total shipment cost to Chicago Tools):

Cost of doing business

Total warehouse cost	$ 400,000.00
Total inbound cost	$ 519,664.13
Total outbound cost	$ 544,106.94
Total Cost	**$ 1,463,771.08**
(Objective function)	

Figure 16 - Model output for objective function (2 operational warehouses)

<u>Recommendation from optimized model -</u> What is the optimized cost and number of warehouses suggested by the optimized model?

Figure 17 - Visual depiction of the optimized flow for Chicago Tool

Simplex LP model suggested that Chicago Tools should keep two warehouses open i.e. Calgary and Markham (one being on the west and another on the east respectively). Also, Sacramento plant should supply to Calgary and Litchfield should supply to Markham. Additionally, these two warehouses can ship to customers located close to them and minimize the shipment cost. E.g. Calgary should handle customers in Calgary, Clavet, Coquitlam, Winnipeg. Markham should ship to customers on the east coast like Charlottetown, Halifax, Markham, Moncton, Montreal, St Johns and Winnipeg. Notice that Winnipeg is central to both warehouse locations hence the model recommends that both warehouses can ship to Winnipeg. However, it gets four times larger shipment from Calgary than Markham. This could be because Sacramento has fully utilized its plant production capacity. We would like to further explore this and check if we can have just one warehouse shipping to Winnipeg by increasing Sacramento production capacity as it is slightly closer to Calgary than Markham.

***Sensitivity analysis*:**

To answer What-if questions of Chicago Tools, we utilized SolverTable's One-way and Two-way analysis along with our understanding of problematic shipment routes that we gathered during data analysis. Below are the observations and recommendations:

1. What-if we have all 4 warehouses functional or open?

   SolverTable One-way analysis helps us understand that the most optimal solution would have only 2 warehouses open as they can rightly cater to demands of all customers, in fact even after doing that, Litchfield still has some leftover capacity of about 1,196,533 lbs which can be further utilized in case of last minute demand by customers of Markham.

   If we have only one warehouse open, then it would have the maximum shipment cost because of the extreme locations of customers. Further, with 3 or 4 warehouses being open cost is higher owing to the warehouse operating cost which is $200,000 per warehouse. The total shipment weights handled by 2 warehouses and 4 warehouses is the same just the distribution changes slightly (refer to the screenshots below), so there is no logical sense to keep accruing extra cost for additional 2 warehouses.

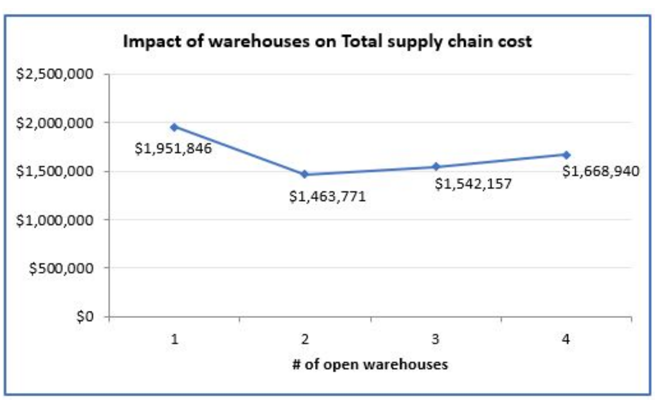


Figure 18 - Plot to showcase differences in cost for different number of operational warehouses

Two operational warehouses vs. four operational warehouses:

Weight (lbs.)	Warehouses			
Plants	Calgary	Coquitlam	Markham	Moncton
Litchfield	0	0	3703467	0
Sacramento	2000000	0	0	0

Weight (lbs.)	Warehouses			
Row Labels	Calgary	Coquitlam	Markham	Moncton
Litchfield	0	0	2449808	1253659
Sacramento	1513183	486817	0	0

Figure 19 - Inbound model outputs for two and four operational warehouses

Two warehouses were able to fulfill orders from ten customers within optimal distance. However, with 4 warehouses we are still handling the same demand of customers and in fact Coquitlam is only shipping to customers in Coquitlam which was earlier handled by Calgary. Further, Moncton and Markham being in proximity to each other, splits the customers which Markham was handling individually earlier. This is not adding any shipment advantage rather is adding additional warehouse running cost which increases the overall cost by $205,168.83 i.e. ($1,668,939.91 - $1,463,771.08).

Weight (lbs.)	Customers										
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg	Total
Calgary	900258	0	199291	486817	0	0	0	0	0	413634	2000000
Coquitlam	0	0	0	0	0	0	0	0	0	0	0
Markham	0	39120	0	0	599628	1340685	386168	998830	228743	110293	3703467
Moncton	0	0	0	0	0	0	0	0	0	0	0
										Total demand =	5.703.467.00

Weight (lbs.)	Customers										
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg	Total
Calgary	900258	0	199291	0	0	0	0	0	0	413634	1513183
Coquitlam	0	0	0	486817	0	0	0	0	0	0	486817
Markham	0	0	0	0	0	1340685	0	998830	0	110293	2449808
Moncton	0	39120	0	0	599628	0	386168	0	228743	0	1253659
										Total demand =	5,703,467.00

Figure 20 - Outbound model outputs for two and four operational warehouses

2. What if we have additional demand from the west coast that must be handled by Sacramento plant considering only two warehouses are functional. Is it possible to increase production capacity without impacting the overall cost?

<u>We propose two possible solutions to this scenario:</u>

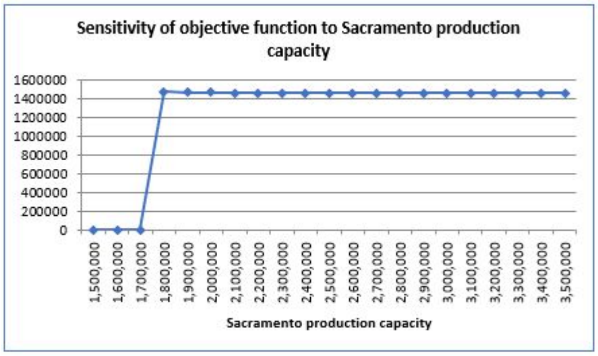
a. Chicago Tools can increase production capacity of Sacramento plant to 2,200,000 lbs along with decreasing production capacity of Litchfield plant to 3,600,000 lbs as it was underutilized in the optimal model. This would lead to reduction in overall cost by $4,124.96 i.e. $1,463,771.08 - $1,459,646.12. Additionally, this would mean that Winnipeg Customer is now being supplied by warehouses connected to Sacramento plant and not by both Litchfield and Sacramento. Overall demand handled stays the same and surplus capacity exists in both the plants to handle unplanned shipments.

Weight (lbs.)	Customers										
Warehouses	Calgary	Charlottetown	Clavet	Coquitlam	Halifax	Markham	Moncton	Montreal	St Johns	Winnipeg	Total
Calgary	900258	0	199291	486817	0	0	0	0	0	523927	2110293
Coquitlam	0	0	0	0	0	0	0	0	0	0	0
Markham	0	39120	0	0	599628	1340685	386168	998830	228743	0	3593174
Moncton	0	0	0	0	0	0	0	0	0	0	0
										Total demand =	5,703,467.00

Constraints:	L.H.S		R.H.S	Surplus Capacity
Supply constraints:				
Maximum production capacity of Litchfied Plant	3,593,174	<=	3,600,000	6,826
Maximum production capacity of Sacramento Pla	2,110,293	<=	2,200,000	89,707

Figure 21 - Outbound model outputs and constraints

b. Chicago Tools can also plan to increase production capacity of Sacramento and Litchfield by a large range if the plant's infrastructure will sustain it and they have sufficient storage space to accommodate surplus goods produced. Sacramento plant can have an increased capacity in the range of 2,200,000 to 3,500,000 lbs along with Litchfield plant having capacity as 3,600,000 to 5,600,000 lbs. With this approach Chicago Tools can decide to increase production capacity for both the plants and still have a reduced cost i.e. $1,459,646.12 which is $4,124.96 less than the proposed optimal cost. The overall distribution of shipment weights will stay the same for all customers as provided in option ‘a’, however, the surplus capacity for both plants would keep on increasing as we increase the production capacity based on the range provided.



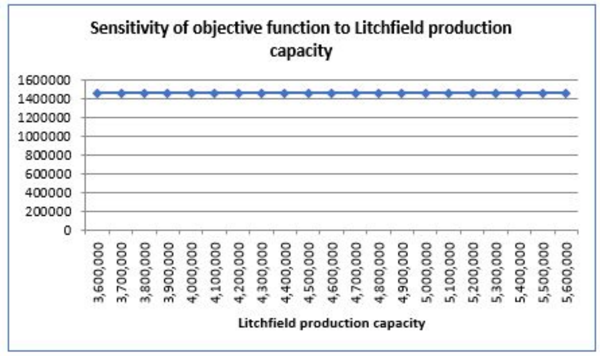


Figure 22 - Two-way sensitivity analysis

Note that with the given understanding this solution seems to give the same optimal cost for even a larger capacity limit, however, it would not be so as there would be storage cost associated with the growing surplus. We currently are not aware of the storage details (area/cost) and hence cannot conclude with certainty. This option makes business sense only if Chicago Tools has plans of expansion and procurement of more customers which would bring shipment into churn and lead to less storage. Otherwise, it would possibly add to the overall cost owing to larger storage needs.

Conclusion

With the information and constraints provided by Chicago Tools, our optimization model predicted the lowest overall supply chain cost by keeping just 2 warehouses active and optimizing the weights being shipped and the origin-destination routes. This led to a decrease in overall fixed warehouse operating cost (i.e. $200,000/warehouse and reduced shipment costs owing to non-optimal shipment routes). We now recommend to just keep 2 warehouses active (i.e. Calgary and Markham) which would supply customers in its proximity except for Winnipeg which is getting shipment from both the warehouse owing to saturation of capacity at Sacramento plant. So, to slightly reduce the cost further, we would recommend an increase in production capacity by 10% i.e. 200,000 lbs for Sacramento plant. Alongside, Chicago Tools can choose to keep Litchfield capacity as is i.e. 4,900,000 lbs or reduce it to as low as 3,600,000 lbs. This would lead to Winnipeg getting shipment from just one warehouse, Calgary (supplied by Sacramento) and in turn reduce additional $4,124.96 from the supply chain cost. This would also keep them prepared for surprise orders from customers as both the plants will have surplus produce in storage.

Further, we would propose an update to the current optimization model once Chicago Tools have more information around other variables like additional new customers, storage space and storage cost at each plant and warehouses. This will help us optimize the supply chain further with possible additional savings in the overall costs.

Bibliography

1. Taha, Hamdy A. *Operations Research*. MacMillan Publishing Company, 1992.

   Referred for: Learning the Network modelling and its formulation.

2. Watson, Michael, et al. *Supply Chain Network Design*. FT Press, 2012.

   Referred for: Supply chain domain knowledge specifically for Inbound and outbound transportation flows plus assumptions on the transportation cost.

3. Wikipedia reference for Big M method logic and calculations.

4. Winston, Wayne L., and S. Christian Albright. *Practical Management Science*. Cengage Learning, 2018.

   Referred for: General reference to MILP models and calculations.

Appendices

Network diagrams in Tableau

1. Baseline model:

   https://us-west-2b.online.tableau.com/#/site/networkdiagram/workbooks/279208?:origin=card_share_link

2. Optimized baseline model:

   https://us-west-2b.online.tableau.com/#/site/networkdiagram/workbooks/279211?:origin=card_share_link

3. Optimized number of Warehouses:

   https://us-west-2b.online.tableau.com/#/site/networkdiagram/workbooks/279212?:origin=card_share_link