Fall 2001

Freightliner LLC Manufacturing Optimization

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ETM
ENGINEERING & TECHNOLOGY MANAGEMENT

Title: Freightliner LLC Manufacturing Optimization

Course Title: Operations Research
Course Number: EMGT 540
Instructor: Anderson
Term: Fall
Year: 2001
Author(s): Compton, Jefferis, Mat-Amin, Ngoussou

ETM OFFICE USE ONLY	
Report No.:	
Type:	Student Project
Note:	

Abstract

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Freightliner LLC

Manufacturing Optimization

EMGT 540/ FALL 2001

OPERATIONS RESEARCH

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Executive Summary

Freightliner LLC has been producing innovative products since 1942 for the trucking industry. Following a 1981 acquisition by Daimler-Benz AG, Freightliner has steadily gained market share through acquisition and fleet sales. Following record production in 1999 at maximum yield levels, year 2000 hit the heavy truck market especially hard. High diesel fuel prices, low used truck values, and a slowing economy were just a few reasons for reduced truck sales.

Through Q1 of 2001, heavy vehicle production was down 54% compared to 2000 in attempts of lowering inventory amounts. In this new market, capacity is no longer the overall manufacturing constraint. The overriding concern instead is minimizing manufacturing costs to optimize profits.

This report details a manufacturing tool created to determine optimal allocation of build quantities at the six Freightliner LLC truck plants. This tool was created using linear programming in Excel with VBA. The four part minimization of 1) direct labor; 2) variable non-manpower costs; 3) fixed plant costs; and 4) shipping costs along with sales and plant capacity constraints were modeled for twelve quarters of production. The tool was then used to analyze three scenarios, including I) a labor rate increase, II) a non-labor variable rate increase, and III) a shift in production volume.

While this linear program was a simplified model of the actual Freightliner manufacturing system, it is capable of showing trends based on changes in constraints. The goal to create a working manufacturing optimization tool was achieved. This project affirmed the concepts of Linear Programming including model objective, constraints, decision variables, and sensitivity analysis in a real world manufacturing optimization setting.

Freightliner LLC History

Freightliner began in the late 1930s when Consolidated Freightways founder Leland James saw the need for a lighter, stronger, and more economical truck. After unsuccessfully convincing a manufacturer to tackle his revolutionary truck design, James set out to build his own. In 1942 the first Freightliner nameplate appeared, laying the cornerstone of innovation and a custom approach to heavy truck manufacturing.

Early Freightliner on Swan Island

In 1981 Freightliner took their first leap towards globalization through a partnership with then Daimler-Benz AG. This partnership heightened the pace of heavy truck technology for Freightliner. In 1991 Freightliner began to leverage Daimler-Benz resources to export trucks. Through the Mercedes-Benz trucks dealer networks, Freightliner trucks entered new markets in Mexico, Asia, and the Middle East to name just a few. [1]

Freightliner's push in the early nineties was towards increased market share. Their U.S. heavy truck market share grew from 16.3% in 1988 to over 25% in 1995. [1] This remarkable growth was made possible through a combination of large fleet sales and custom design, supported by Mercedes-Benz financing. To date the Freightliner nameplate remains the leader in market share and technical innovation. [1]

In 1995 Freightliner extended their market coverage by acquiring Freightliner Custom Chassis Corporation, gaining entry into Class 4-7 bus and chassis market. That same year Freightliner purchased American LaFrance, a company with 167 years of experience in fire trucks and emergency vehicles. Freightliner also acquired Thomas Built to extend their bus market share.

As the 20th century was waning, DaimlerChrysler and Freightliner realized the good times in the North American truck market could not last forever. After all, the supposed seven-year cycle had been skipped nearly twice. So after expanding into new markets of medium duty chassis and rescue vehicles, it was time for Freightliner to expand their core business, Class 8 trucks. In 1997, Freightliner purchased the Ford Heavy Truck. This product was renamed Sterling in the Freightliner family, filling the niche of vocational trucks and budget tractors.

Freightliner continued the buying spree with the acquisition of Western Star Holdings, a custom heavy truck manufacturer based in Kelowna, Canada. With around 1-2% of the U.S. Class 8 market share, Western Star was by no means a threat. Western Star does have a strong history in vocational and off-road applications such as logging and oil field service to add to the Freightliner family. [1]

Industry Status

1999 was a record year for the trucking industry. The Class 8 heavy-duty industry sold 262,000 trucks in the U.S. and 180,000 medium-duty trucks. Freightliner and its divisions built and delivered nearly 200,000 commercial vehicles with total revenue of $11.2 billion. That was up over 60% from 1998 sales of 128,000 vehicles with $7.5 billion in revenue. [2] To keep pace with demand, Freightliner often ran truck plants around the clock, six and sometimes seven days a week. Manufacturing was capacity constrained and all emphasis was place on volume.

Regardless of surviving the Y2K scares, the trucking industry was quite unsettled in 2000. Driver shortages across the country were limiting fleet growth. Diesel prices raised to all time levels, which forced trucking companies to cut cost and limit new acquisitions. Used truck values were falling below acceptable trade-in levels on new equipment. Add in a slowing economy, and a recipe for disaster was brewing for the trucking industry. Top it off with extensive Freightliner guaranteed lease residuals, and now disaster was setting in.

During the last quarter of 2000, a substantial drop in vehicle production occurred in North America in order to reduce excessive inventories of new vehicles and adjust the operations to lower sales. The significantly lower production rate continued through 2001. The North America production of heavy vehicles during the first quarter of 2001 accounted to some 39,000 units, which was a decrease of 54% compared to the same period the previous year. [3]

It is estimated that the North America production of heavy vehicles will remain on the same low level for the rest of the year with a slight increase towards the end of 2002. All truck makers have been affected by the sudden change due to the dramatic collapse of the heavy-truck market in North America. OEMs are no longer capacity constrained. Significant cost cutting measures are being implemented to keep the company from too much red ink.

Most OEMs operate one or two manufacturing plants, where build scheduling is a simple decision of build or idle. Freightliner however has many plants that build many different product models. This creates more opportunity in a capacity un-constrained market to shift production to minimize manufacturing costs.

Project Definition

With a corporation as large as Freightliner, there were many opportunities for optimization modeling. Our group decided to select a manufacturing tool to minimize manufacturing costs by allocating build quantities to the overall most efficient plants. The time span selected was three years (2002-2004) broken into 12 quarters. The model used was linear programming with binary linking constraints written in Excel. VBA code was added to facilitate repetition of the solver for the twelve quarters analyzed.

Six Freightliner LLC manufacturing plants were analyzed, with three U.S. plants; Portland, OR, Cleveland, NC, and Mt Holly, NC; two Canadian plants; St. Thomas, Ontario and Kelowna, B.C.; and one Mexican plant in Santiago Tianguistenco. Ten products were included in this model, representing the majority of Freightliner sales. Those product lines were Century, Columbia, FLD, Argosy, Western Star, Military, HN80, Acterra, FLN, and M2. Not all truck models are built at all plants however, so optimization is limited. Table 1 below shows the compatible model and manufacturing plants in shaded cells. For example, there is tooling available to build the Columbia product in Portland, Cleveland, and Mexico. The Argosy however can only be built in Cleveland.

Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2
Portland, OR										
Cleveland, NC										
Mt Holly, NC										
St Thomas, Canada										
Kelowna, Canada										
Santiago, Mexico										

Table 1: Manufacturing Matrix

The objective of the model is to minimize manufacturing costs in the four parts of 1) direct labor costs; 2) variable non-manpower; 3) fixed plant costs; and 4) shipping costs. Direct labor costs were the average hourly rate of each plant, as shown in Table 2.

Plant #	Name	Location	Hourly Rate
001	PTMP	Portland, OR	$ 35.26
004	CTMP	Cleveland, NC	$ 32.75
017	MTH	Mt Holly, NC	$ 33.25
030	STT	St Thomas, Canada	$ 26.80
055	Kelowna	Kelowna, Canada	$ 21.80
065	Santiago	Santiago, Mexico	$ 9.20

Table 2: Direct Labor Costs

The total hourly manufacturing cost was found using the following algorithm:

- Total Hourly Cost = Sumproduct [Hourly rate, Sumproduct(model hours by plant, models built by plant)]

The second component of variable non-manpower costs include plant consumables and manufacturing supplies. These total costs are amortized to a per truck average and totaled:

- Total Variable Costs = Sumproduct [Per Unit Rate, Sum(model produced by plant)]

The third component of fixed plant costs include salaried manpower, plant overhead, and depreciation, shown below in Table 3 along with non-manpower costs, and written out as:

- Total Fixed Plant Costs = Sumproduct [Binary plant open/closed, Sum(fixed costs)]

Plant #	Name	Location	Per Unit Rate	Fixed Non-Manpower Per Quarter	Fixed Manpower Per Quarter	Depreciation Per Quarter
001	PTMP	Portland, OR	$ 648.00	$ 1,609,375	$ 2,031,250	$ 1,062,625
004	CTMP	Cleveland, NC	$ 426.00	$ 3,281,250	$ 2,875,000	$ 2,681,250
017	MTH	Mt Holly, NC	$ 513.00	$ 2,597,825	$ 3,425,950	$ 1,063,075
030	STT	St Thomas, Canada	$ 452.00	$ 2,343,750	$ 1,650,000	$ 1,321,525
055	Kelowna	Kelowna, Canada	$ 942.00	$ 543,450	$ 688,450	$ 575,200
065	Santiago	Santiago, Mexico	$ 709.00	$ 750,000	$ 1,312,500	$ 1,420,000

Table 3: Variable Non-Manpower and Fixed Plant Costs

The final portion of cost analyzed was shipping. This modeled the cost of shipping trucks from the plants to dealerships across the world. To keep the model relatively simple, North America was broken into eleven regions with a twelfth region for export sales. Shipping costs were assigned to each region from each plant. Table 4 below lists the shipping costs per unit.

Region	PTMP	CTMP	MTH	STT	Kelowna	Santiago
Western Canada	$ 400	$ 1,100	$ 1,100	$ 600	$ 200	$ 3,800
Eastern Canada	$ 1,050	$ 900	$ 900	$ 200	$ 600	$ 3,700
North West	$ 225	$ 1,550	$ 1,100	$ 1,000	$ 325	$ 2,300
West	$ 475	$ 1,450	$ 900	$ 1,050	$ 700	$ 2,100
Mountain	$ 650	$ 1,350	$ 850	$ 950	$ 850	$ 2,050
Central	$ 850	$ 750	$ 700	$ 800	$ 1,000	$ 1,900
South	$ 600	$ 500	$ 450	$ 850	$ 975	$ 1,750
North East	$ 1,150	$ 510	$ 500	$ 700	$ 1,300	$ 2,450
East	$ 950	$ 350	$ 350	$ 650	$ 1,150	$ 2,400
South East	$ 1,100	$ 250	$ 250	$ 900	$ 1,200	$ 2,300
Mexico	$ 1,325	$ 1,680	$ 1,500	$ 1,850	$ 1,900	$ 250
Export	$ 1,850	$ 2,600	$ 2,600	$ 3,200	$ 3,300	$ 3,500

Table 4: Shipping Costs

Another table detailed expected sales volume for each model per region. The algorithm for the total sales costs using these expected sales was:

- Total Shipping Cost = Sum of Regions {[Cost per plant by region] x [Sumproduct(Models built per plant, model demand per region)]}

The first constraint placed upon the model was expected sales and plant capacity. The sales impact upon this model did not include inventory costs. Since manufacturing was the scope of the model, it was assumed that all sales per quarter would be required and shipped from the plant to a dealer. The expected sales for the three-year period are shown in Table 5.

	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Sales
2002 - Q1	8,200	9,000	12,000	500	500	1,000	8,500	11,000	16,500	500	67,700
2002 - Q2	8,200	14,300	11,500	520	600	1,200	8,000	12,500	15,500	500	72,820
2002 - Q3	8,400	14,600	11,000	530	650	1,100	8,250	12,900	14,000	2,500	73,930
2002 - Q4	8,500	15,200	10,000	500	700	900	6,500	17,000	8,000	4,500	71,800
2003 - Q1	8,750	16,800	9,250	510	800	950	5,000	17,500	0	15,000	74,560
2003 - Q2	9,400	17,600	8,000	510	950	1,100	2,500	17,500	0	17,500	75,060
2003 - Q3	9,800	19,150	6,500	550	1,100	1,100	0	18,000	0	22,500	78,700
2003 - Q4	10,500	19,850	5,000	600	1,300	1,000	0	16,500	0	22,500	77,250
2004 - Q1	11,000	24,000	0	610	1,900	1,150	0	17,000	0	22,500	78,160
2004 - Q2	12,000	25,500	0	600	2,100	1,050	0	17,250	0	23,000	81,500
2004 - Q3	12,500	27,000	0	620	2,150	1,050	0	17,300	0	23,000	83,620
2004 - Q4	12,500	29,500	0	620	2,300	900	0	17,400	0	23,500	86,720

Table 5: Model Sales per Quarter

Of importance is the FLD, HN80, and FLN which at various quarters have no sales. These three models are aging products that will be replaced with sales of five of the remaining products. The second constraint was plant capacity per quarter. This data is shown below in Table 6.

Plant #	Name	Location	Capacity
001	PTMP	Portland, OR	20,000
004	CTMP	Cleveland, NC	31,000
017	MTH	Mt Holly, NC	24,250
030	STT	St Thomas, Canada	26,000
055	Kelowna	Kelowna, Canada	4,500
065	Santiago	Santiago, Mexico	12,500

Table 6: Plant Capacity

The final model constraint consisted of a linking constraint with a binary decision variable. This binary was used to model plant activity, and either add fixed plant costs or not. The big M variable chose was 50,000 to properly link plant hours greater than one to a binary variable of one, and vice-versa for a binary output of zero.

The decision variables for number of a model built at a certain plant were previously shown in Table 1. These were not constrained as integers; the design of the LP however naturally led to near integer values selected. The other decision variables as mentioned were the binary decisions to idle or activate a certain plant. Appendix I provides more details on variables and equations for the optimization model.

Initial Results

Since the model was set up to optimize quarterly, a VBA macro was written to automate the solver and step through all twelve quarters of expected sales. The total optimized manufacturing cost for these twelve quarters was $3.64 billion. For space considerations, these results are included in Appendix II.

In general the results show that Cleveland is more efficient than Portland and therefore carries the majority of production for the common truck models. All Century models of the twelve quarters were built in Cleveland. All Columbia trucks prior to Q9 are also built in Cleveland. In this quarter Cleveland hits capacity constraints and must ship some Columbia volume to Mexico, which has available capacity due to FLD phase out. Both Military and Western Star products are optimized by being produced in Kelowna. All Argosy and HN80 are built at Cleveland and St. Thomas respectively, with the latter also building all Acterra product. Prior to phase-out in Q5, all FLN are built in Mt Holly, as are all M2 product.

This model provides an optimized manufacturing schedule based on a limited number of constraints. In reality, a plant must either stay busy quarter to quarter or close for long periods. In other words, a plant cannot switch quarterly from idle to active status. What the model does inform is if Century and Columbia production is split between Cleveland and Portland to keep both plants active, significant addition manufacturing costs are accrued.

Scenario Analysis

To test out the tool, three scenarios were analyzed; I) a labor rate increase, II) a non-labor variable rate increase, and III) a shift in production volume. The goal was to test the optimization model for sensitivity to changing constraints and objective function coefficients. All scenarios were hypothetical what-if type parameters with no specific ties to actual corporate directions.

Scenario I was titled *Union Negotiations*. Assuming the North Carolina unions were actively negotiating wage increases, this scenario determined at what level of rate increase will production be shifted elsewhere to maintain minimum manufacturing costs. To model this, the hourly rate values were increased for both Cleveland and Mt Holly from 5-40% in increments of 5%. Plant utilization percent of the six plants were then plotted against these percent increases.

Figure 1 shows the plant utilization at a 10% increase in North Carolina labor. This plot is identical to the plot of no labor increase. There continues to be no change in plant utilization until the 25% increase, as shown in Figure 2 below.

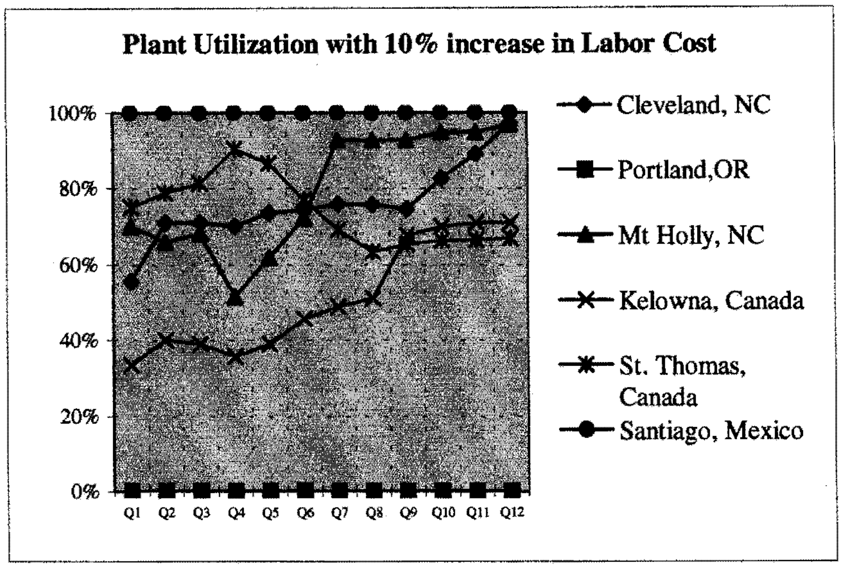

Figure 1: Plant Utilization at 10% Increase

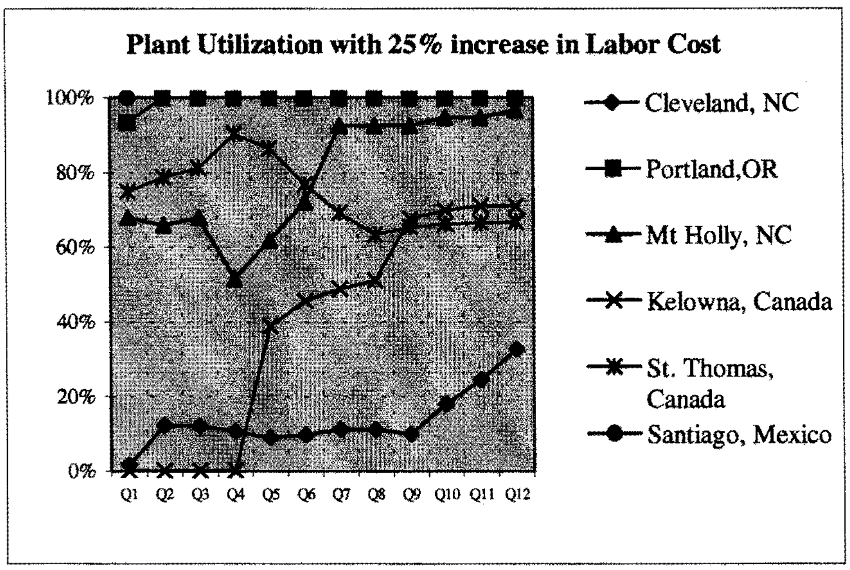

Figure 2: Plant Utilization at 25% Increase

These plots show that between 20% and 25% labor rate increase of the North Carolina truck plants, there is a dramatic shift in production for the optimized model. Basically, Cleveland loses production of the Century and Columbia models to Portland. An interesting effect of opening Portland is the additional shift of Military and Western Star product from Kelowna to Portland as well. In Q5 Portland capacity is overcome and these products are sent back to Kelowna in the optimized model.

Note also that Mt Holly is not affected by this labor increase as plant utilization remains unchanged through a 25% increase. This is due to the capacity constraints, shipping costs, and labor costs for building medium duty product in Mexico.

Scenario II was titled *Natural Disaster*, attempting to model increases in supply costs due to a continued increase in U.S. Eastern seaboard tropical storms. Again this scenario affected only the two North Carolina plants, raising the non-labor variable rates by 10, 100, 150, 175, and 200%. Figures 3 and 4 show plant utilization for these rate increases at the Mt Holly and Cleveland truck plants.

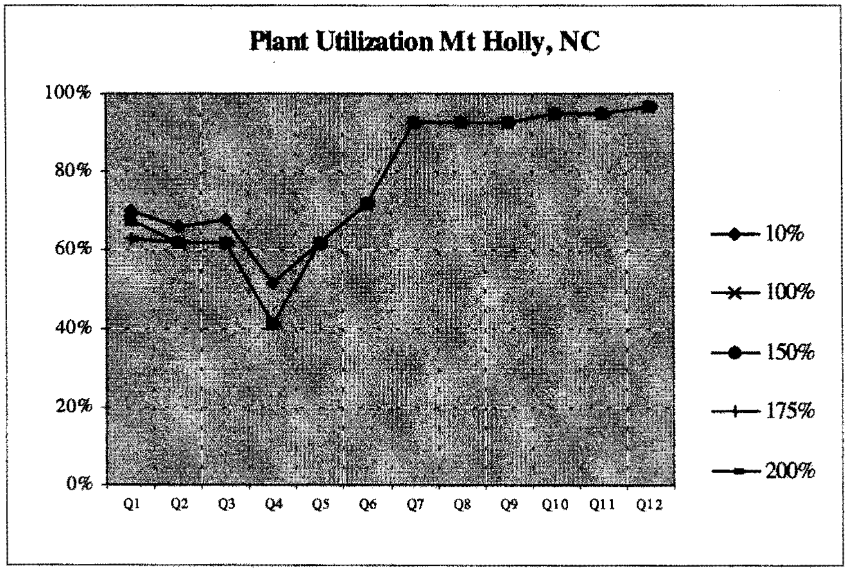

Figure 3: Mt Holly Plant Utilization; Scenario II

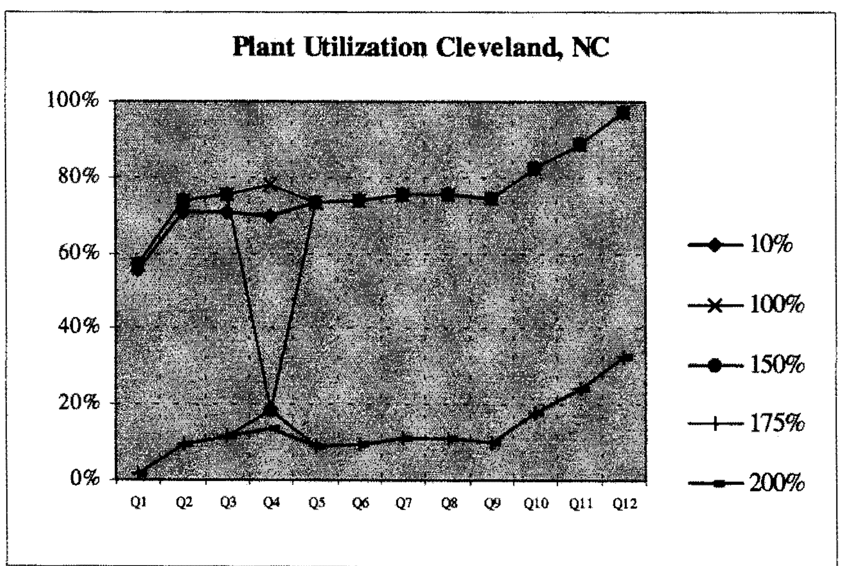

Figure 4: Cleveland Plant Utilization; Scenario II

Figure 3 illustrates that Mt Holly has little sensitivity to non-labor variable costs. If these costs are increased 100% or more, there is a slight production shift in the optimized model for Q1 through Q4. From Q5 on however, there is no net change in Mt Holly Production.

Cleveland however shows more dramatic changes. At a 150% increase, there is a large shift in Q4 from Cleveland to Portland. This shifts back in Q5 however due to the end of FLN production and available Mexico production for the Columbia model. This shift to Mexico shifts production back to Cleveland from Portland based on fixed overhead costs. At 175% increase, Cleveland production is drastically decreased as it is now less expensive to produce trucks in Portland.

The final scenario was *America Goes to War*, with the United States entering a World War III in June of 2002. This scenario had America slipping into a recession under uncertainty of how long the war campaign would last. This recession would cause trucking companies to drastically reduce the number of new truck and tractor purchases. It was assumed also that Military sales would spike 300% in Q3 and remain 40% above average over the remaining nine quarters. Figures 5 and 6 below again detail plant utilization at Mt Holly and Cleveland.

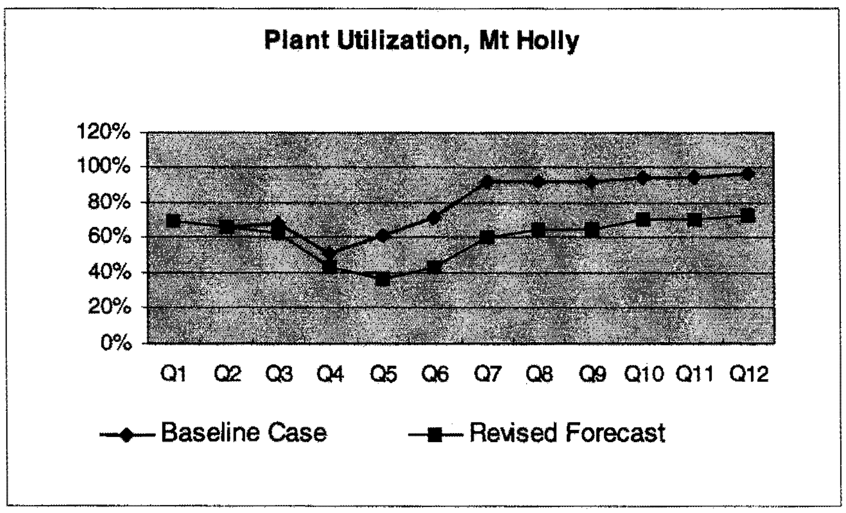

Figure 5: Mt Holly Plant Utilization; Scenario III

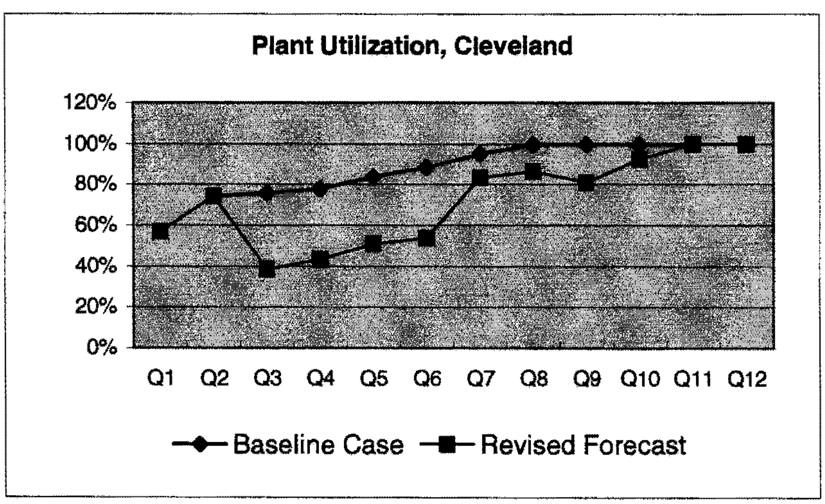

Figure 6: Cleveland Plant Utilization; Scenario III

Mt Holly plant will see only a minimal utilization decrease initially under Scenario III. In Q5 there is a substantial drop in utilization, a trend that is maintained throughout the remaining seven quarters.

Cleveland again has a more interesting reaction to Scenario III. Due to the dependence on Class 8 tractor production, Cleveland immediately loses production in Q3. There is a substantially large recovery however in Q7; in this quarter the FLD production is shifted from Mexico for cost optimality. Due to initial capacity constraints, Cleveland returns to 100% utilization in Q11 and Q12 even with Class 8 production decreases and no production of Military product.

Conclusions

In summary, a manufacturing tool to determine build quantity allocation at the six Freightliner LLC truck plants was created using linear programming in Excel with VBA. The four part minimization of 1) direct labor; 2) variable non-manpower; 3) fixed plant costs; and 4) shipping costs along with sales and plant capacity constraints were modeled for twelve quarters of production. This tool was then used to analyze three scenarios, including I) a labor rate increase, II) a non-labor variable rate increase, and III) a shift in production volume.

While this linear program was a simplified model of the actual Freightliner manufacturing system, it did give meaningful results. It may be too rough for exact allocation of build quantities, yet it is capable of showing trends based on changes in constraints.

Future work to this model would include additional constraints to more closely represent actual manufacturing conditions. For example, there needs to be a minimal production quantity per quarter for a plant that is open for an extended period of time. This would reduce the large shift of quantities from location to location and smooth out the plant utilization results. Additional VBA programming could also be performed to create a better user interface and to automate output data and graphs. Finally, a DEA comparing similar plants would be a useful tool to add.

The goal to create a working manufacturing optimization tool was achieved. In doing so, a useful optimization model was created for use at Freightliner LLC. This project affirmed the concepts of Linear Programming including model objective, constraints, decision variables, and sensitivity analysis in a real world manufacturing optimization setting.

Bibliography

[1] Freightliner Trucks Website: http://www.freightlinertrucks.com

[2] Special Report: Birth of a Global Company: http://www.daimlerchrysler.com

[3] Financial Reports analysts: http://www.haldex.com

Appendix I: Equations for Optimization Model:

Variables:

Y_{ij} – Where Y is the number of units (trucks), $_i$ is the plant where X is produced, and $_j$ is the model (truck).
X_i – Where X is a binary variable stating whether the plant is Active or Idle.
Z_{ijk} – Where Z is the number of units, I is the plant, j is the model, k is the region shipped to

<u>Plants:</u>
1 – Portland, OR
2 – Cleveland, NC
3 – Mt. Holly, NC
4 – St. Thomas, Canada
5 - Kelowna, Canada
6 - Santiago, Mexico

<u>Models</u>:
1 – Century
2 – Columbia
3 – FLD
4 – Argosy
5 – Western Star
6 – Military
7 – HN80
8 – Acterra
9 – FLN
10 – M2

The objective function is to minimize total costs including fixed, variable, and shipping costs

$$\text{MIN: } \left.\begin{aligned}
&\$1{,}609{,}375X_1 + \$3{,}281{,}250X_2 + \$2{,}599{,}825X_3 + \$2{,}343{,}750X_4 + \$543{,}450X_5 + \$750{,}000X_6 \\
&+ \$2{,}031{,}250X_1 + \$2{,}875{,}000X_2 + \$3{,}425{,}950X_3 + \$1{,}650{,}000X_4 + \$688{,}450X_5 + \$1{,}312{,}500X_6 \\
&+ \$1{,}062{,}625X_1 + \$2{,}681{,}250X_2 + \$1{,}063{,}075X_3 + \$1{,}321{,}525X_4 + \$575{,}200X_5 + \$1{,}420{,}000X_6
\end{aligned}\right\} \text{Fixed Costs}$$

$$\left.\begin{aligned}
&+\$648Y_{11} + \$648Y_{12} + \$648Y_{13} + \$648Y_{15} + \$648Y_{16} + \\
&\$426Y_{21} + \$426Y_{22} + \$426Y_{23} + \$426Y_{24} + \\
&\$513Y_{39} + \$513Y_{310} + \\
&\$452Y_{47} + \$452Y_{48} + \\
&\$942Y_{55} + \$942Y_{56} \\
&\$709Y_{62} + \$709Y_{63} + \$709Y_{68} + \$709Y_{69}
\end{aligned}\right\} \text{Variable – Per Unit}$$

$$\left.\begin{aligned}
&+(84.9*\$35.26*Y_{11}) + (83.2*\$35.26*Y_{12}) + (89.8*\$35.26*Y_{13}) + (126*35.26*Y_{15}) + \\
&(120.6*\$35.26*Y_{16}) \\
&+(82.5*\$32.75*Y_{21}) + (79.4*\$32.75*Y_{22}) + (88.6*\$32.75*Y_{23}) + (96.3*\$32.75*Y_{24}) \\
&+(62.8*\$33.25*Y_{39}) + (53.6*\$33.25*Y_{310}) \\
&+(86.5*\$26.80*Y_{47}) + (71.3*\$26.80*Y_{48}) \\
&+(136.2*\$21.80*Y_{55}) + (145.2*\$21.8*Y_{56}) \\
&+ (135*\$9.20*Y_{62}) + (142.3*\$9.20*Y_{63}) + (82*\$9.20*Y68) + (67.9*\$9.20*Y_{69})
\end{aligned}\right\} \text{Variable – Labor Hours}$$

$$\left.\begin{aligned}
&+(\$400*Z_{111}) + (\$1050*Z_{112}) + (\$225*Z_{113}) + (\$475*Z_{114}) + (\$650*Z_{115}) + (\$850*Z_{116}) \\
&+ (\$600*Z_{117}) + (\$1150*Z_{118}) + (\$950*Z_{119}) + (\$1100*Z_{1110}) + (\$1325*Z_{1111}) \\
&+ (\$1850*Z_{1112}) + +(\$400*Z_{121}) + (\$1050*Z_{122}) + (\$225*Z_{123}) + (\$475*Z_{124}) + \\
&(\$650*Z_{125}) + (\$850*Z_{126}) + (\$600*Z_{127}) + (\$1150*Z_{128}) + (\$950*Z_{129}) + (\$1100*Z_{1210}) \\
&+ (\$1325*Z_{1211}) + (\$1850*Z_{1212}) + (\$400*Z_{131}) + (\$1050*Z_{132}) + (\$225*Z_{133}) + \\
&(\$475*Z_{134}) + (\$650*Z_{135}) + (\$850*Z_{136}) + (\$600*Z_{137}) + (\$1150*Z_{138}) + (\$950*Z_{139}) + \\
&(\$1100*Z_{1310}) + (\$1325*Z_{1311}) + (\$1850*Z_{1312}) + (\$400*Z_{161}) + (\$1050*Z_{162}) + \\
&(\$225*Z_{163}) + (\$475*Z_{164}) + (\$650*Z_{165}) + (\$850*Z_{166}) + (\$600*Z_{167}) + (\$1150*Z_{168}) \\
&+ (\$950*Z_{169}) + (\$1100*Z_{1610}) + (\$1325*Z_{1611}) + (\$1850*Z_{1612}) + \text{etc for every plant} \\
&\text{and model}
\end{aligned}\right\} \text{Shipping Costs}$$

Constraints:

$$\left.\begin{array}{l}
Y_{11} + Y_{12} + Y_{13} + Y_{14} + Y_{15} + Y_{16} + Y_{17} + Y_{18} + Y_{19} + Y_{110} <= 20{,}000 \\
Y_{21} + Y_{22} + Y_{23} + Y_{24} + Y_{25} + Y_{26} + Y_{27} + Y_{28} + Y_{29} + Y_{210} <= 31{,}000 \\
Y_{31} + Y_{32} + Y_{33} + Y_{34} + Y_{35} + Y_{36} + Y_{37} + Y_{38} + Y_{39} + Y_{310} <= 24{,}250 \\
Y_{41} + Y_{42} + Y_{43} + Y_{44} + Y_{45} + Y_{46} + Y_{47} + Y_{48} + Y_{49} + Y_{410} <= 26{,}000 \\
Y_{51} + Y_{52} + Y_{53} + Y_{54} + Y_{55} + Y_{56} + Y_{57} + Y_{58} + Y_{59} + Y_{510} <= 2{,}500 \\
Y_{61} + Y_{62} + Y_{63} + Y_{64} + Y_{65} + Y_{66} + Y_{67} + Y_{68} + Y_{69} + Y_{610} <= 12{,}500
\end{array}\right\} \text{Capacity}$$

$$\left.\begin{array}{l}
Y_{11} + Y_{21} + Y_{31} + Y_{41} + Y_{51} + Y_{61} = \text{Demand for that Quarter} \\
Y_{12} + Y_{22} + Y_{32} + Y_{42} + Y_{52} + Y_{62} = \text{Demand for that Quarter} \\
Y_{13} + Y_{23} + Y_{33} + Y_{43} + Y_{53} + Y_{63} = \text{Demand for that Quarter} \\
Y_{14} + Y_{24} + Y_{34} + Y_{44} + Y_{54} + Y_{64} = \text{Demand for that Quarter} \\
Y_{15} + Y_{25} + Y_{35} + Y_{45} + Y_{55} + Y_{65} = \text{Demand for that Quarter} \\
Y_{16} + Y_{26} + Y_{36} + Y_{46} + Y_{56} + Y_{66} = \text{Demand for that Quarter} \\
Y_{17} + Y_{27} + Y_{37} + Y_{47} + Y_{57} + Y_{67} = \text{Demand for that Quarter} \\
Y_{18} + Y_{28} + Y_{38} + Y_{48} + Y_{58} + Y_{68} = \text{Demand for that Quarter} \\
Y_{19} + Y_{29} + Y_{39} + Y_{49} + Y_{59} + Y_{69} = \text{Demand for that Quarter} \\
Y_{110} + Y_{210} + Y_{310} + Y_{410} + Y_{510} + Y_{610} = \text{Demand for that Quarter}
\end{array}\right\} \text{Production must meet demand}$$

All Xi variables are binary
All X & Y variables >= 0

** Implied Constraints are that production is only available in certain plants for certain models.

Appendix II: ne Results

Quarter 1

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 272,101,903
004	CTMP	Cleveland, NC	8,200	9,000	-	500	-	-	-	-	-	-	17,700	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	16,500	500	17,000	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	8,500	11,000	-	-	19,500	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	500	1,000	-	-	-	-	1,500	4,500	
065	Santiago	Santiago, Mexico	-	-	12,000	-	-	-	-	-	-	-	12,000	12,500	
		Total Production	8,200	9,000	12,000	500	500	1,000	8,500	11,000	16,500	500	Total Production		
		Demand	8,200	9,000	12,000	500	500	1,000	8,500	11,000	16,500	500	67,700		

Quarter 2

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 292,766,242
004	CTMP	Cleveland, NC	8,200	14,300	-	520	-	-	-	-	-	-	23,020	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	15,500	500	16,000	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	8,000	12,500	-	-	20,500	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	600	1,200	-	-	-	-	1,800	4,500	
065	Santiago	Santiago, Mexico	-	-	11,500	-	-	-	-	-	-	-	11,500	12,500	
		Total Production	8,200	14,300	11,500	520	600	1,200	8,000	12,500	15,500	500	Total Production		
		Demand	8,200	14,300	11,500	520	600	1,200	8,000	12,500	15,500	500	72,820		

Quarter 3

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 295,600,273
004	CTMP	Cleveland, NC	8,400	14,600	-	530	-	-	-	-	-	-	23,530	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	14,000	2,500	16,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	8,250	12,900	-	-	21,150	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	650	1,100	-	-	-	-	1,750	4,500	
065	Santiago	Santiago, Mexico	-	-	11,000	-	-	-	-	-	-	-	11,000	12,500	
		Total Production	8,400	14,600	11,000	530	650	1,100	8,250	12,900	14,000	2,500	Total Production		
		Demand	8,400	14,600	11,000	530	650	1,100	8,250	12,900	14,000	2,500	73,930		

Quarter 4

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 286,910,542
004	CTMP	Cleveland, NC	8,500	15,200	-	500	-	-	-	-	-	-	24,200	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	8,000	4,500	12,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	6,500	17,000	-	-	23,500	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	700	900	-	-	-	-	1,600	4,500	
065	Santiago	Santiago, Mexico	-	-	10,000	-	-	-	-	-	-	-	10,000	12,500	
		Total Production	8,500	15,200	10,000	500	700	900	6,500	17,000	8,000	4,500	Total Production		
		Demand	8,500	15,200	10,000	500	700	900	6,500	17,000	8,000	4,500	71,800		

Quarter 5

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 293,740,413
004	CTMP	Cleveland, NC	8,750	16,800	-	510	-	-	-	-	-	-	26,060	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	15,000	15,000	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	5,000	17,500	-	-	22,500	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	800	950	-	-	-	-	1,750	4,500	
065	Santiago	Santiago, Mexico	-	-	9,250	-	-	-	-	-	-	-	9,250	12,500	
		Total Production	8,750	16,800	9,250	510	800	950	5,000	17,500	(0)	15,000	Total Production		
		Demand	8,750	16,800	9,250	510	800	950	5,000	17,500	-	15,000	74,560		

Quarter 6

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 295,534,456
004	CTMP	Cleveland, NC	9,400	17,600	-	510	-	-	-	-	-	-	27,510	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	17,500	17,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	2,500	17,500	-	-	20,000	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	950	1,100	-	-	-	-	2,050	4,500	
065	Santiago	Santiago, Mexico	-	-	8,000	-	-	-	-	-	-	-	8,000	12,500	
		Total Production	9,400	17,600	8,000	510	950	1,100	2,500	17,500	(0)	17,500	Total Production		
		Demand	9,400	17,600	8,000	510	950	1,100	2,500	17,500	-	17,500	75,060		

Appendix II: ne Results

Quarter 7

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 306,845,473
004	CTMP	Cleveland, NC	9,800	19,150	-	550	-	-	-	-	-	-	29,500	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	22,500	22,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	0	18,000	-	-	18,000	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	1,100	1,100	-	-	-	-	2,200	4,500	
065	Santiago	Santiago, Mexico	-	-	6,500	-	-	-	-	-	-	-	6,500	12,500	
		Total Production	9,800	19,150	6,500	550	1,100	1,100	0	18,000	(0)	22,500	Total Production		
		Demand	9,800	19,150	6,500	550	1,100	1,100	-	18,000	-	22,500	78,700		

Quarter 8

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 302,302,810
004	CTMP	Cleveland, NC	10,500	19,850	-	600	-	-	-	-	-	-	30,950	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	22,500	22,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	0	16,500	-	-	16,500	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	1,300	1,000	-	-	-	-	2,300	4,500	
065	Santiago	Santiago, Mexico	-	-	5,000	-	-	-	-	-	-	-	5,000	12,500	
		Total Production	10,500	19,850	5,000	600	1,300	1,000	0	16,500	(0)	22,500	Total Production		
		Demand	10,500	19,850	5,000	600	1,300	1,000	-	16,500	-	22,500	77,250		

Quarter 9

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 306,147,820
004	CTMP	Cleveland, NC	11,000	19,390	-	610	-	-	-	-	-	-	31,000	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	22,500	22,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	0	17,000	-	-	17,000	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	1,900	1,150	-	-	-	-	3,050	4,500	
065	Santiago	Santiago, Mexico	-	4,610	(0)	-	-	-	-	-	-	-	4,610	12,500	
		Total Production	11,000	24,000	(0)	610	1,900	1,150	0	17,000	(0)	22,500	Total Production		
		Demand	11,000	24,000	-	610	1,900	1,150	-	17,000	-	22,500	78,160		

Quarter 10

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 318,775,112
004	CTMP	Cleveland, NC	12,000	18,400	-	600	-	-	-	-	-	-	31,000	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	23,000	23,000	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	0	17,250	-	-	17,250	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	2,100	1,050	-	-	-	-	3,150	4,500	
065	Santiago	Santiago, Mexico	-	7,100	(0)	-	-	-	-	-	-	-	7,100	12,500	
		Total Production	12,000	25,500	(0)	600	2,100	1,050	0	17,250	(0)	23,000	Total Production		
		Demand	12,000	25,500	-	600	2,100	1,050	-	17,250	-	23,000	81,500		

Quarter 11

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 327,275,028
004	CTMP	Cleveland, NC	12,500	17,880	-	620	-	-	-	-	-	-	31,000	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	23,000	23,000	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	0	17,300	-	-	17,300	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	2,150	1,050	-	-	-	-	3,200	4,500	
065	Santiago	Santiago, Mexico	-	9,120	(0)	-	-	-	-	-	-	-	9,120	12,500	
		Total Production	12,500	27,000	(0)	620	2,150	1,050	0	17,300	(0)	23,000	Total Production		
		Demand	12,500	27,000	-	620	2,150	1,050	-	17,300	-	23,000	83,620		

Quarter 12

Plant #	Name	Location	Century	Columbia	FLD	Argosy	Western Star	Military	HN80	Acterra	FLN	M2	Total Unit Production	Capacity	Manufacturing Cost
001	PTMP	Portland, OR	-	-	-	-	-	-	-	-	-	-	-	20,000	$ 338,983,573
004	CTMP	Cleveland, NC	12,500	17,880	-	620	-	-	-	-	-	-	31,000	31,000	
017	MTH	Mt Holly, NC	-	-	-	-	-	-	-	-	(0)	23,500	23,500	24,250	
030	STT	St Thomas, Canada	-	-	-	-	-	-	0	17,400	-	-	17,400	26,000	
055	Kelowna	Kelowna, Canada	-	-	-	-	2,300	900	-	-	-	-	3,200	4,500	
065	Santiago	Santiago, Mexico	-	11,620	(0)	-	-	-	-	-	-	-	11,620	12,500	
		Total Production	12,500	29,500	(0)	620	2,300	900	0	17,400	(0)	23,500	Total Production		
		Demand	12,500	29,500	-	620	2,300	900	-	17,400	-	23,500	86,720		