

# Plant Location Modelling for the Concrete and Asphalt Industries

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## Abstract

The Auckland concrete and asphalt industries currently face substantial change in the supply of their principal ingredient, aggregate rock, as key aggregate quarries have been mined to completion and are scheduled to close. Consequent economic and environmental conditions mean a number of Auckland concrete and asphalt plants are in turn expected to close, with new plants being built in more suitable locations, and possible modifications made to remaining plants for increased capacity. This paper discusses a transportation and blending model used to assist two Auckland companies: Firth Industries with regards to the location of their ready-mix concrete plants, and Works Infrastructure for the location of their asphalt plants. The model provides simulation and analysis of the expected costs involved with each of the various scenarios of plant locations currently under consideration by the respective companies, accounting for the raw material, blending and transportation costs. The choice of plant location is shown to impact decisions throughout the industry supply chain, influencing the selection of raw material suppliers, along with the assignment of customer orders to plants for final delivery.

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## 1 Background

Facility location is extremely relevant for the Auckland concrete and asphalt industries due to their dependence on quarries for aggregate. The industry is currently facing significant changes in the supply of aggregate from the central Auckland region, as key aggregate quarries, including the Lunn Avenue quarry operated in Mt Wellington by Winstone Aggregates, have been mined to completion and are planned for closure within the year. This signifies major impact, as the Mt Wellington quarry has been New Zealand's largest aggregate quarry, producing up to two million tonnes per year [1] with up to fifteen hundred truck movements per day.

The impact of the quarry closures is very much amplified by the significance of transportation as a cost factor in the industry. The current trend for aggregate resources to be at increased distances from urban centres [2] requires transporting aggregate long distances, leading to substantial increases in cost. Transporting a typical 25 tonne truckload costs about 10 cents per tonne per km. An extra 25 km can double the cost to the consumer [3].

Closure of the quarries, amongst other factors, foreshadows expectation that downstream Auckland concrete and asphalt plants are in turn expected to close, with

new plants being built in more suitable locations, along with possible modifications to remaining plants to increase capacity.

This paper discusses modelling exercises carried out for two organisations within the industry, the first of which is a comprehensive model for Firth Industries to model the location of ‘ready-mix’ concrete plants, from which ready mixed concrete is delivered around Auckland. Firth currently operate eight ready-mix certified concrete plants to service the Auckland area. These plants take raw material of aggregate and cement, and produce certified concrete, which Firth then delivers to satisfy demand within the Auckland region.

The second application is with Works Infrastructure (formed from the Ministry of Works) with regards to the location of their asphalt plants. Works currently operate two asphalt plants in Auckland, on either side of the Lunn Avenue quarry in Mt Wellington. At each plant, aggregate is mixed with bitumen to produce asphalt. This asphalt is then either transported and used by Works on projects such as road maintenance, or sold as gate-sales, to be picked up and transported by customers to their place of application.

## 2 Plant Location Modelling

The situation currently faced by the industry has provoked a strategic planning exercise and critical review of plant location throughout Auckland. With transportation cost being the most influential factor influencing plant location, a simulation model was requested to quantify the expected transportation costs arising from adoption of each of a number of plant location scenarios under consideration. Note that the selection of candidate plant locations is limited by urban development and considerations of ‘not in my back yard,’ restricting these new industrial plants to consented locations within the Auckland region.

To meet this need, an optimisation model has been created which draws on the framework of operations research problems for facility location, transportation, transshipment, blending and shortest path optimisation. By optimising the transportation and production decisions using a given combination of plant locations, the model can provide a simulation of the anticipated decisions and expected cost under that scenario.

The overall process can be seen in Figure 1.

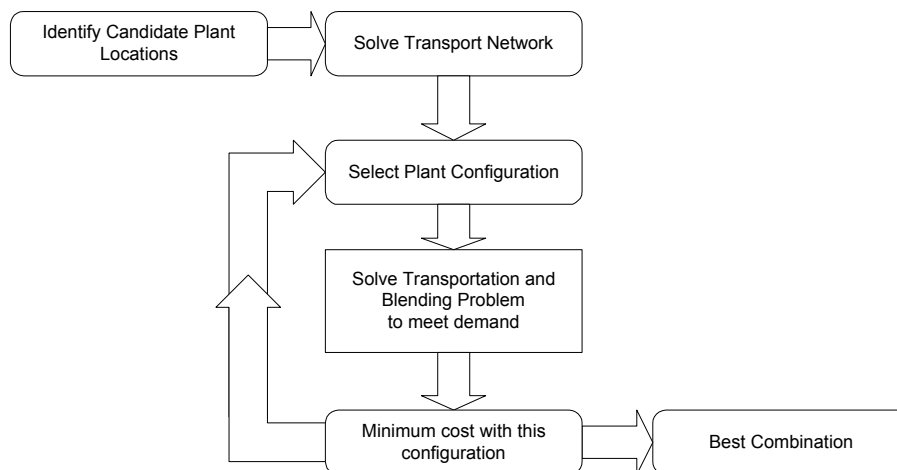


Figure 1: Model Solution Process

The solution process for analysing plant locations is based around selecting scenarios of supplier and plant facility locations, and then solving the transportation and blending problem to discover the costs expected under each scenario. This process enables flexible analysis under a number of cases, to investigate a range of scenarios or options associated with possible plant locations and production capacities.

The end objective of the exercise is to enable industry to determine the optimal locations for a given number of plants in order to minimise total cost of transportation and production of product within the region to service demand efficiently at the lowest cost. Auxiliary to this is the impact on the selection of quarries and suppliers for streamlined procurement of each aggregate.

Note that a standard facility location model was not adopted for this application because (a) management sought the ability to determine anticipated costs involved for each of the predetermined combinations under consideration, as opposed to a single overall minimum, and (b) the trivial number of scenarios under review could allow complete enumeration, should such a minimum be required. Therefore use of a transportation and blending linear programming approach was selected to provide more accurate modelling than the standard facility location formulation.

## 2.1 Transportation and Blending Optimisation

The core of the model, subsequently referred to as the *TransBlend* model, is based around a transshipment problem of moving raw materials to plants, producing final product at the plant, and then delivering on to demand nodes. This problem is optimised for every combination of plant locations specified, and can be approximated as a multi-commodity transshipment flow through a set of plants, as depicted in Figure 2.

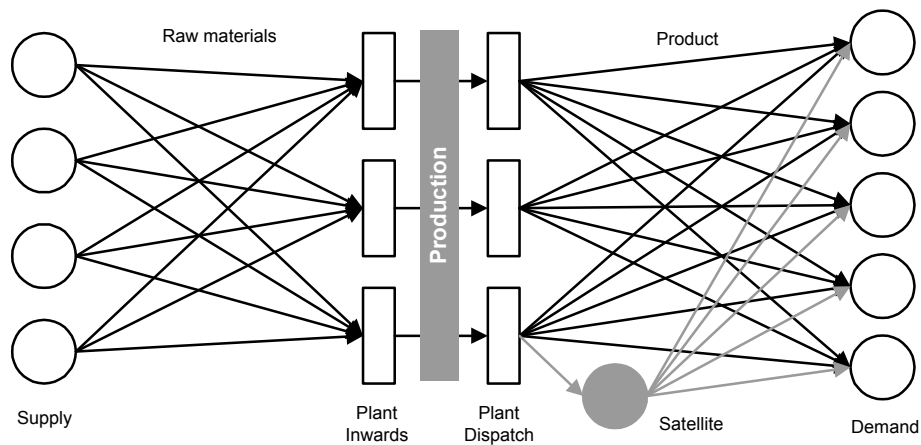


Figure 2: Schematic of the Transportation and Blending Problem

For each combination of plant locations, the TransBlend model seeks to optimise transportation and blending decisions, accounting for supply of raw materials, blending of materials into final product, and delivery of product to customer demand nodes. The demand nodes for the problem were modelled as a set of approximately 400 point locations around the region, at the centre of each of the Auckland suburbs and at significant demand locations such as Auckland airport.

Within this problem, there is an additional consideration for the use of ‘satellite’ plants, essentially holding bins for storing product that may allow non-industrial locations close to demand centres to provide product that has been produced at other plants.

## 2.2 Road Network Model

The transportation and blending problem requires a set of delivery distances as a parameter input. Initial solutions for the model were based on crow-flight distances between the source and destination nodes. Although providing a prototype model very quickly, it became obvious that these distances were too simplistic for the application, aggravated by the unusual geography of the Auckland region arising from the large Waitemata and Manukau harbours, whereby two locations could appear in close proximity by crow-flight distance, but in reality are separated by water, and require travelling around the perimeter of the harbour.

To address this inaccuracy, a road network transportation model was implemented, using shortest path information to model distances between nodes on the network. This was based on a node-arc network of the main arterials of the Auckland region (refer Figure 3). Dijkstra's algorithm [4] for finding shortest paths was implemented to compute the network distances. The network model (which is relatively constant) could be pre-solved, and then used as a constant input for solving each of the facility location scenarios in the transportation and blending optimisation.



Figure 3: Auckland Road Network Showing Discretised Location Nodes

### 3 Formulation

Decision Variables:

- $u_{ijt}$  = number of truckloads from plant  $i$  to demand location  $j$  during time period  $t$
- $v_{ijt}$  = volume of product delivered from plant  $i$  to demand location  $j$  during time period  $t$
- $x_{lki}$  = total volume of raw material  $l$  delivered from supplier  $k$  to plant  $i$
- $y_{ijt}$  = volume of product transported from plant  $i$  to plant  $j$  during time period  $t$
- $z_{it}$  = volume of product produced at plant  $i$  during time period  $t$

Data Parameters:

- $d_{ij}$  = the distance between any location  $i$  and any location  $j$
- $c_d$  = truck cost per unit of distance for plant to demand deliveries
- $c_s$  = truck cost per unit of distance for supplier to plant deliveries
- $c_h$  = truck cost per unit of distance for transshipment between plants
- $a_d$  = truck capacity for plant to demand deliveries
- $a_s$  = truck capacity for supplier to plant deliveries
- $a_h$  = truck capacity for transshipment between plants
- $p_i$  = production cost per unit of product at plant  $i$
- $w_i$  = production capacity at plant  $i$  per hour
- $b_{lk}$  = material cost per unit of material  $l$  from supplier  $k$
- $r_l$  = number of units of material  $l$  required for production of one unit of product
- $q_{jt}$  = volume of product demanded at demand location  $j$  during time period  $t$
- $\mathbf{r}_{jt}$  = minimum number of deliveries required at demand location  $j$  during time period  $t$
- $m$  = number of demand locations
- $n$  = number of plants
- $o$  = number of material types
- $s$  = number of supply locations
- $\mathbf{t}$  = number of hours per time period
- $T$  = number of time periods

Minimise

$$\sum_{k=1}^s \sum_{i=1}^n \sum_{l=1}^o \left( \left( \frac{c_s}{a_s} d_{ki} + b_{lk} \right) x_{lki} \right) + \sum_{t=1}^T \left( \sum_{i=1}^n p_i z_{it} + \frac{c_h}{a_h} \sum_{i=1}^n \sum_{j=1}^n d_{ij} y_{ijt} + c_d \sum_{i=1}^n \sum_{j=1}^m d_{ij} u_{ijt} \right) \quad (1)$$

Subject to

$$\sum_{i=1}^n v_{ijt} \geq q_{jt} \quad \forall j \in \text{demand locations}, \forall t = 1, 2, \dots, T \quad (2)$$

$$\sum_{i=1}^n u_{ijt} \geq \mathbf{r}_{jt} \quad \forall j \in \text{demand locations}, \forall t = 1, 2, \dots, T \quad (3)$$

$$\sum_{j=1}^m v_{ijt} + \sum_{k=1}^n y_{ikt} \leq z_{it} + \sum_{l=1}^n y_{lit} \quad \forall i \in \text{plants}, \forall t = 1, 2, \dots, T \quad (4)$$

$$z_{it} \leq \mathbf{t} w_i \quad \forall i \in \text{plants}, \forall t = 1, 2, \dots, T \quad (5)$$

$$v_{ijt} \leq a_d u_{ijt} \quad \forall i \in \text{plants}, \forall j \in \text{demand locations}, \forall t = 1, 2, \dots, T \quad (6)$$

$$\sum_{t=1}^T r_l z_{it} \leq \sum_{k=1}^s x_{lki} \quad \forall i \in \text{plants}, \forall l \in \text{materials} \quad (7)$$

$$u_{ijt}, v_{ijt}, x_{lki}, y_{ijt}, z_{it} \geq 0$$

Explanation of Equations:

(1) Minimisation Objective

The first term is the delivery and purchase cost of raw materials, formulated as the summation over all suppliers, plants and materials, of the volume of raw material delivered ( $x$ ) multiplied by the delivery distance ( $d$ ), scaled by the cost per truck load divided by volume per truck ( $c_s/a_s$ ). Volume is also multiplied by the purchase cost ( $b$ ) for the material.

The second term is the total production cost, as a summation over all plants of the cost per unit ( $p$ ) multiplied by the number of units produced ( $z$ ).

The third term is the cost for transshipment of product between plants, as the summation, over all transshipment links, of the delivery distance ( $d$ ) by the volume transhipped ( $y$ ) scaled by cost per truck divided by truck size ( $c_h/a_h$ ).

The fourth term is the cost of delivery to customers, a summation over all delivery links, of the cost per truckload ( $c_d$ ) by the number of truckloads ( $u$ ) by the delivery distance ( $d$ ).

- (2) Ensure that the volume demand ( $q$ ) at each demand node  $j$  is met by the total volume delivered ( $v$ ) from all plants.
- (3) Ensure that the number of deliveries requested ( $r$ ) at each node  $j$  are met by the total number of deliveries ( $u$ ) from all plants.
- (4) Ensure that the volume of product leaving a plant via transshipment ( $y$ ) or delivery to customers ( $v$ ) does not exceed the amount of volume produced ( $z$ ) at the plant and transhipped into the plant.
- (5) The amount of volume produced ( $z$ ) at each plant can not exceed the capacity per hour multiplied by the number of operating hours in the demand period ( $t$ ).
- (6) Ensure that the volume delivered ( $v$ ) to each customer from each plant does not exceed delivery truck size ( $a_d$ ) multiplied by the number of trucks ( $u$ ) performing the delivery.
- (7) Each unit of product produced ( $z$ ) requires a recipe amount of ( $r_l$ ) units of material  $l$ . Therefore, this constraint ensures that the volume of material delivered ( $x$ ) meets the required quantity ( $r_l z$ ) at each plant.

## 4 Implementation

The TransBlend model was implemented as a Microsoft Windows application codenamed the *BANANA<sup>1</sup> Facility Location Model*, or *LocationModel* for short. This application comprises a comprehensive user interface and visualisation tool created using Visual C++, utilising a CPLEX server as the back-end solver. The LocationModel application is used to establish model parameters, solve the transportation network, retrieve and manipulate demand data, and reconstruct it in AMPL [5] format for solution by the CPLEX solver. Output from the CPLEX optimisation is then read by the LocationModel application and used to visualise results and produce reports on the most appropriate plant configuration.

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<sup>1</sup> BANANA – “Build Absolutely Nothing Anywhere Near Anybody” refers to the pertinent problem faced by the industry with regards to the limitations on plant location options. This acronym is creeping into mainstream use (refer [www.pseudodictionary.com](http://www.pseudodictionary.com)) and somehow found its way into the application title.

The LocationModel program generates data for the CPLEX solver in three data sets, containing demand data, transportation distances, and model parameters respectively. Separating the data into three components allows for easy comparison between a selection of plant configuration scenarios running against different combinations of model parameters, or transport weights. For example, a given set of plants can be analysed using shortest path weights based on road distance, and then the transport data interchanged for the shortest path weights based on shortest travel time, while the other data sets remain constant.

An extremely useful feature of the LocationModel software is its ability to visualise delivery decisions on screen, so that the optimisation results and decisions can be verified and analysed, demonstrating the credibility of the result sets. A typical screen output of the visualisation system is shown in Figure 4.

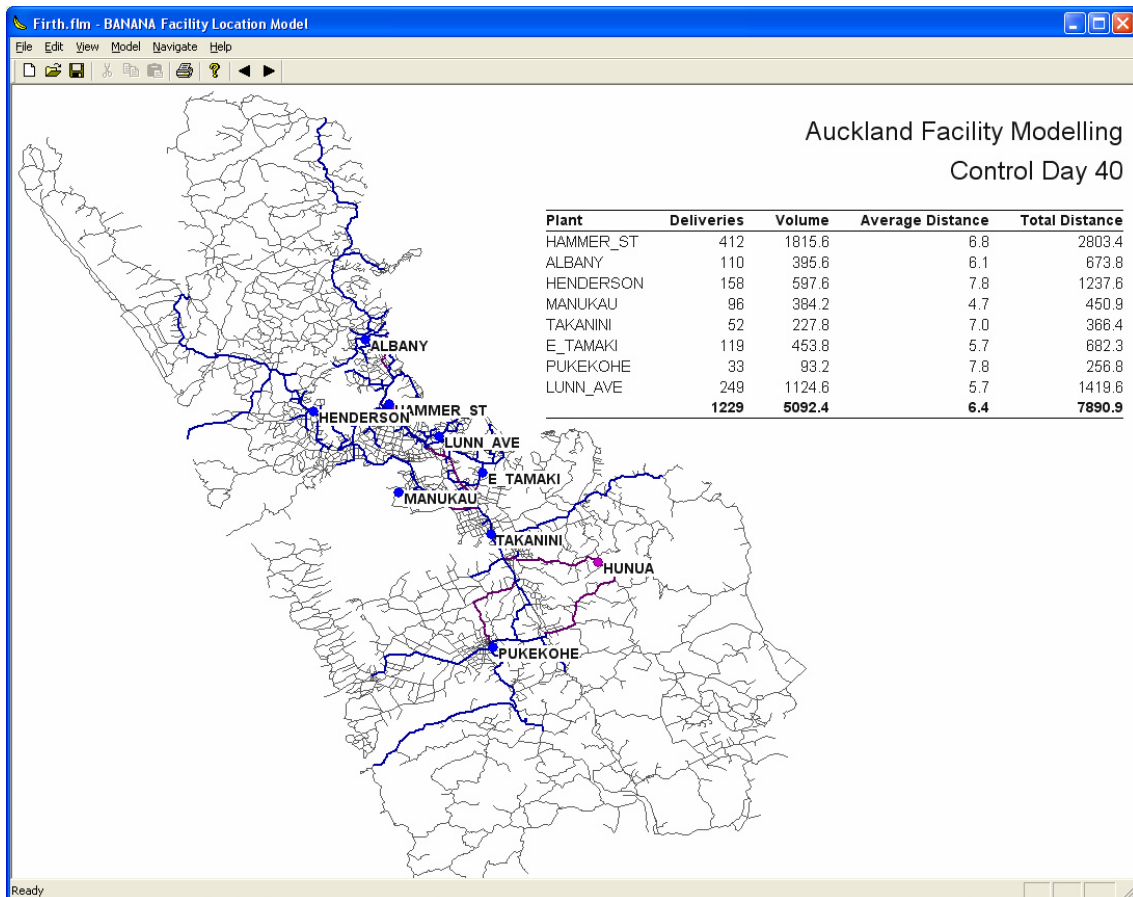


Figure 4: Screen Display of the LocationModel program

This figure displays the delivery decisions made under the scenario 'Control' to meet the demand requirements of day 40 of the provided demand data set. The transportation paths that are used in this scenario and time frame are plotted on the network map to show the exact paths that the solver has selected for the given configuration of plants. When using a colour screen, transportation from suppliers to plants, transshipment between plants, and final delivery to customers are each shown in different colours so that the locations of costs can be quickly seen in a visual format.

The LocationModel software also provides comprehensive reporting for comparison of plant configurations, along with cost summaries, and tabulation of the proportion of days in the data period for which each configuration was recommended as the lowest cost option. Each of these reports can be exported to Microsoft Excel.

## 5 Parameter Data

Parameters and data for the TransBlend model were sourced from each of the companies, to provide parameters for truck capacities and costs, production capacities, material costs and supplier locations, and distances. For comprehensive demand data, the front-end system was designed to import sales location information from historical sales and delivery data. For the Firth ready-mix plant location exercise, data was made available for some 130,000 sales orders, with associated street addresses around Auckland. These addresses were converted into approximately 400 discrete point locations, in most cases, centred on the suburb location of the address. Using historical sales data, the TransBlend model can provide information quantifying the cost of meeting demand, had the plants been located in each of the provided location configurations. By a similar method, future demand modelling can be performed by the input of forecast demand data into the model.

Plant production capacity constraints were modelled through analysis of plant production curves, to assign sales orders to periods of the day. It became evident that plant capacity is an issue only during peak hours, typically mid morning or mid afternoon. Figure 5 shows the typical distribution of deliveries by time of day for one of Firth Industries' concrete plants.

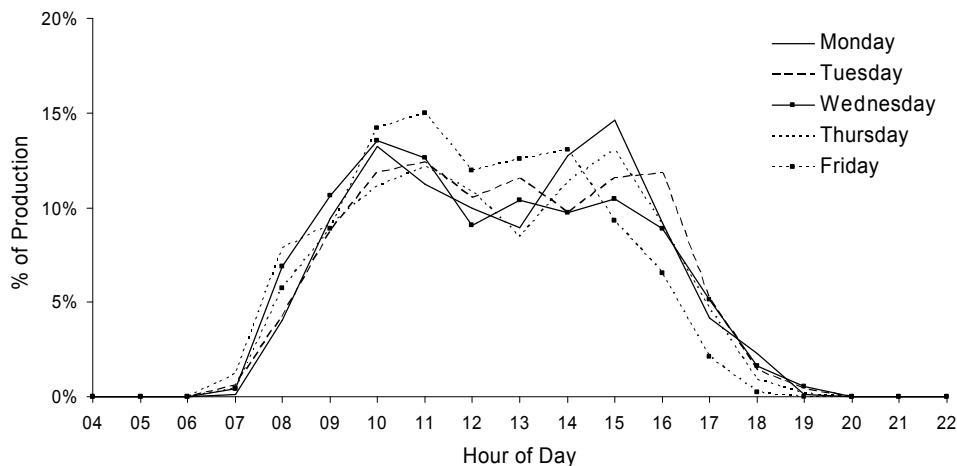


Figure 5: Average Distribution of Plant Production Level by Hour of Day

Because of this feature of peak production plant capacity, the TransBlend model was amended to differentiate between times of day, so that each period contained both Peak and Off Peak components. To implement more accurate capacity constraints, a percentage of the average daily demand was allocated to be met during the peak period. In the case of Firth Industries, a further constraint was added, to require that at least 15% of daily demand must be met in one peak hour.

## 6 Results

The model has been used for a variety of analysis purposes, for analysing the impact of plant closures, production capacity increases and evaluation of potential sites for new plants. Firth Industries use the optimisation model, connected to a set of Microsoft Excel spreadsheets, to associate the transportation costs found by the TransBlend model



with required capital expenditure, resource compliance costs and associated expenses. The information is then used to present proposed actions to senior management. This draws on output from the LocationModel program, including a series of tabulated reports and graphical road network diagrams to demonstrate credibility of the results.

The flexibility of the model has allowed analysis of different combinations under consideration, providing a valuable tool for ‘what if’ analysis of different scenarios.

Furthermore, the choice of plant location has been observed to impact decisions throughout the region, so that a plant closure does not affect just the area localised to the plant closure, but affects decisions throughout the modelled region, influencing the selection of raw material suppliers, along with the assignment of customer orders to plants for final delivery.

To verify the Firth Industries model, scenario analysis was carried out with regards to the closure of the East Tamaki ready-mix plant. This closure had recently been carried out by Firth, and numerical results from the model related closely to real-world observations, especially for the increase in delivery cost associated with deliveries to East Auckland, providing credibility for model parameters for other analysis exercises.

A typical summary report from the model is shown in Figure 6, giving a summary of the delivery cost associated with the specified control scenario.

### Results Summary Control

Plant Name	No. Deliveries	Volume Delivered	Total Distance	Average Distance	Delivery Cost
HAMMER_ST	43,151	179,015	241,769	5.6	\$846,191
ALBANY	24,845	103,259	191,786	7.7	\$671,250
HENDERSON	19,771	79,619	158,871	8.0	\$556,049
MANUKAU	12,566	56,380	72,887	5.8	\$255,104
TAKANINI	13,861	57,573	97,300	7.0	\$340,551
E_TAMAKI	22,714	94,641	162,927	7.2	\$570,245
PUKEKOHE	7,203	27,252	64,182	8.9	\$224,637
LUNN_AVE	30,601	131,116	169,216	5.5	\$592,257
	<b>174,712</b>	<b>728,855</b>	<b>1,158,938</b>		<b>\$4,056,283</b>

Supplier	Plant	No. Deliveries	Volume	Total Distance	Delivery Cost
AKDTN	HAMMER_ST	1,597	44,754	3,026	\$6,051
HUNUA	HAMMER_ST	12,468	349,079	579,110	\$1,158,219
AKDTN	ALBANY	923	25,815	17,009	\$34,018
HUNUA	ALBANY	7,193	201,355	452,351	\$904,703
AKDTN	HENDERSON	713	19,905	11,096	\$22,192
HUNUA	HENDERSON	5,545	155,257	310,687	\$621,374
AKDTN	MANUKAU	503	14,095	8,883	\$17,766
HUNUA	MANUKAU	3,925	109,940	138,784	\$277,567
AKDTN	TAKANINI	513	14,393	13,722	\$27,444
HUNUA	TAKANINI	4,010	112,267	74,273	\$148,546
AKDTN	E_TAMAKI	845	23,660	16,460	\$32,920
HUNUA	E_TAMAKI	6,590	184,550	193,468	\$386,936
AKDTN	PUKEKOHE	242	6,813	12,083	\$24,166
HUNUA	PUKEKOHE	1,899	53,142	55,905	\$111,810
AKDTN	LUNN_AVE	1,185	33,171	11,399	\$22,798
HUNUA	LUNN_AVE	9,129	255,677	345,081	\$690,163
		<b>57,280</b>	<b>1,603,874</b>	<b>2,243,337</b>	<b>\$4,486,674</b>

Figure 6: Typical Results Summary report generated by the LocationModel program

Summary reports such as this one indicate production quantities allocated to each plant, which has been used as an indication for capacity planning for the plants under different scenarios. The TransBlend model is also being used as a tool to assist with the selection of suppliers, to analyse the impact of established procurement contracts.

## 7 Conclusion

In conclusion, the implementation of this modelling exercise has been an effective means of analysing the impacts of plant location on delivery cost, as a valuable information source for strategic planning. The TransBlend linear program has been used to solve the required transportation and blending problem to allocate production across various combinations of plant locations, and the results have been useful for collation and presentation to senior management for informed strategic decision making.

Implementation of the LocationModel software has enabled integration with real data, for streamlined analysis and visualisation, providing an excellent example of optimisation techniques applied to a practical application in industry.

The model has also indicated that the effect of plant location decisions is not confined to the localised area of the decision, but impacts the whole region. This indicates Firth Industries should continue to use centralised scheduling of production allocation, rather than adopting separate localised scheduling systems, an option currently under consideration.

Finally, the model has been observed to provide realistic optimisation results, and it is anticipated that the model will continue to be used in the future in ongoing modelling activity by industry.

## Acknowledgments

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I would also like to thank Jeffrey Sutton and Robert McKinnon of Firth Industries, and Jag Kulatunga and Matthew Findlay of Works Infrastructure for their assistance in sourcing and compiling data and analysing results for each of their respective companies.

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