Biomass Transportation Model for Intermodal Network

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***Abstract*— Biomass transportation suffers from higher transportation costs and insufficient competition in terms of supply chain providers. The transportation network optimization is somewhat absent in biomass transportation and hence this sector is still subsidized in many states. Transportation network consisting intermodal facility connected with various modes along with various shipment options (direct shipment, transshipment, cross docking, consolidation etc.) among different stages of biomass transportation offer more alternative choices for consideration. Some of the alternative choices induce less cost with longer service time, some provides expedite delivery with higher cost, some maintains similar service level and on time delivery at a reasonable or moderate cost. Proper analysis of various routing options should be done in order to choose the most efficient one. This research develops a generic mathematical model to find out the optimal solution for both minimization of transportation cost and time. In the paper, various solutions obtained from software were analyzed further to find the best alternative. The analysis is done by choosing alternative cost saving routes without affecting the critical time. The recommended solution considers the trade-off between shipment time and transportation cost.**

***Keywords*—** *biomass, intermodal transportation, hub network, direct shipment, cost optimization*

1. Introduction

Ongoing researches in mathematical tools have made it possible to build models and to apply them successfully for optimization of complex logistics systems. This paper describes the development of a mathematical model that optimizes various supply operations of biomass raw material. The supply chain is comprised of four main elements; firstly 'harvesters & collectors', secondly 'storage facilities', thirdly 'preprocessing facilities' and finally transportation to bio-refinery [1]. From the harvesters & collectors sites, biomass raw material can be directly shipped to preprocessing plant otherwise sent to hub or storage facilities. The storage facility may works as a warehouse or a cross docking center. The hub network also plays an important factor in supply chain network. It facilitates consolidation of loads to make the use of economies of scale. Among the bio-refinery plants, there may be some transshipment in case of shortage or surplus of supply.

In case of biomass transportation, three types of transportation modes are considered- trucks, rails and ship/barge. Trucks are suitable for relatively short road transportation both in urban and rural area [2]. Rails are more suitable and cost-effective for relatively mediate-to-long distance transportation if possible where water transport like ship/barge could be the most cost effective for long distance travel [3]. It consumes more time too. In some locations only one mode may be available; while in other locations, using several modes of transportation may be a better option.

This paper has tried to develop a mathematical model utilizing multimodal network, in order to satisfy both of the objectives of minimization of cost and minimization of time. The model considers the collection, transportation and storage of the biomass raw material. In the following section some literature review of mathematical modeling for biomass transportation has been done. After that, the methodology for calculation of transportation cost and transportation time is described. By using optimization tools like excel solver, numbers of unit load to be transported

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through various routes are calculated in order to achieve minimum cost and minimum time. A hypothetical case study regarding production of cellulosic biodiesel from pinewood is developed for doing calculation. Discussion of the results and some recommendation has also been done at the end part of the paper.

2. Literature Review

Biomass includes a complex supply chain of handling and storage which has to be optimized in order to make the production economically feasible [4]. Several simplified general model for the transportation of biomass have been developed. To reduce the operational cost some work has been done to make the raw material handling process more efficient. Cundiff et al. [5] developed a linear programming model for biomass delivery system considering herbaceous biomass. Some models focused on optimal plant size too. Jenkins [6] developed a model to determine optimum plant size for bio-refineries. Jenkins [6] considered depreciation, operating expenses, feedstock delivery and production cost as total production cost. Zhu et al. [7] analyzed various unique characteristics of dedicated biomass logistics system and differentiated the transportation during harvesting season from that of during non-harvesting season.

Singh et al. [8] developed a mathematical model for efficient transportation of biomass assuming circular collection area and considering truck and tractors as modes of transportation. Leboreiro and Hilaly [9] also developed a transportation model along with the production cost model in order to determine optimal plant size for the production of bio-ethanol. Leboreiro and Hilaly [9] follows three types of scheme to calculate the transportation distance; one along radius, other along sides and last one considering winding factor as well as tortuosity factor. He used non dimensional transportation parameter as a basis of model to determine optimum plant size. Eksioglu et al. [10] developed a transportation model for bio-ethanol plant by using mixed integer program. It aimed at minimizing cost considering facility locations and modes of transportation. It also analyzes the feasibility of using barge to transport the raw material and biofuel.

The author of this paper has considered both the transportation cost and the transportation time introducing multiple mode (e.g. truck, rail, and barge) and hub in the traditional transportation model [11]. Instead of using pure hub network system, this paper consider a hybrid hub and spoke network [12] allowing some direct shipment among nodes that facilitate greater service like faster delivery [13]. A mathematical model using mixed integer program has been developed to optimize the total transportation network of biomass raw material. It has combined two objective functions- minimizing transportation cost and minimizing transportation time. Finally, considering a multi-modal transportation network of a bio-diesel industry (hypothetical), this paper compares various transportation routes based on the associated cost and time.

3. Methodology

In order to optimize overall transportation cost and shipment time, separate cost and time equations for each part of the network is necessary. It is important to mention that cost and time objectives are contradictory – i.e. cost reduction will eventually increase the time of shipment and vice versa. After forming the objective function equations, constraints functions are developed. Following sections describes the development of these equations.

3.1 Modeling Transportation Cost

Shipment cost for each mode includes a variable travelling cost 'r_m' (i.e. cost of fuel), variable handling cost 'h_m' (changes proportionately with numbers of unit load '$l_{m(a,b)}$') and fixed order setup cost 'f_m'. Let, $x_{m(a,b)}$ is the distance travelled by biomass from node 'a' to node 'b' using mode 'm'. Shipment cost from node 'a' to node 'b' using mode 'm'-

$$C_m = \{x_{m(a,b)} l_{m(a,b)} r_m + h_m l_{m(a,b)} + f_m\} \qquad (1)$$

Changes of mode enable using low cost mode but it also induce extra handling cost for loading and unloading of goods. Let, $M_{(a,b)}$ be the set of modes of transportation that are being used in route (a,b). Shipment cost using several modes-

$$C_M = \sum_{m\in M_{(a,b)}} \{x_{m(a,b)} l_{m(a,b)} r_m + h_m l_{m(a,b)} + Z_{m(a,b)} f_m\} \quad (2)$$

Where, $Z_{m(a,b)}$ is binary variable that takes value 1 if any load is transported using mode 'm' through route (a,b) otherwise takes the value of 0. It is assumed that constant load is transported throughout various modes. No loss of material occurs during changing of modes. Therefore, considering route (a,b),

$$l_{m(a,b)} = l_{(a,b)} \quad (3)$$

$$Z_{m(a,b)} = Z_{(a,b)} \quad (4)$$

Where, $Z_{(a,b)}$ is binary variable that takes value 1 if any load is transported through route (a,b) otherwise takes the value of 0. Therefore, equation (2) becomes,

$$C_M = \sum_{m\in M_{(a,b)}} \{x_{m(a,b)} l_{(a,b)} r_m + h_m l_{(a,b)} + Z_{(a,b)} f_m\} \quad (5)$$

There are options for using only single mode or some of the available modes as well as using all of the available modes. The various options of routes should be judged based on associated cost and time. If $C_{(a,b)1}$, $C_{(a,b)2}$,....., $C_{(a,b)n}$ are shipment cost associated with various options of routes from a' to 'b', then shipment cost from node 'a' to node 'b',

$$C_{(a,b)n} = \left[\sum_{m\in M_{(a,b)}} \{x_{m(a,b)} l_{(a,b)} r_m + h_m l_{(a,b)} + Z_{(a,b)} f_m\}\right]_n \quad (6)$$

$$\Rightarrow C_{(a,b)n} = \sum_{m\in M_{(a,b)n}} \{x_{m(a,b)n} l_{(a,b)n} r_m + h_m l_{(a,b)n} + Z_{(a,b)n} f_m\} \quad (7)$$

$$C_{(a,b)} = \sum_{1}^{n} C_{(a,b)n} \quad (8)$$

It is assumed that for the shipment between two nodes, only one option of using various modes can be chosen at a time. Considering nodes ‘a’ and ‘b’ [i.e. various routes like (a,b)1, (a,b)2,..., (a,b)n],

$$\sum_{n=1}^{n} Z_{(a,b)n} = 1 \quad (9)$$

Let, I_a is the inventory cost per unit stored load per unit time, H_a is the average holding time, and l_a^I is the no. of unit load of biomass that inventoried at node 'a', then, inventory cost at node 'a' equals $I_a l_a^I H_a$. As transportation cost includes inventory cost and shipment cost, therefore transportation cost for the route (a,b) equals

$$= I_a l_a^I H_a + C_{(a,b)} \quad (10)$$

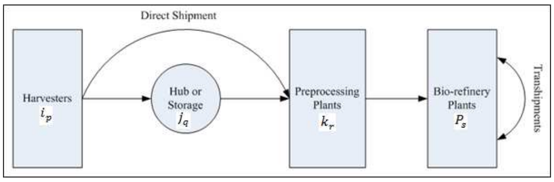

Figure 1. Transportation network of Biomass

If there are 'p' numbers of harvesting sites (i) and 'q' numbers of hub or storage facilities (j), then the set of available transportation routes from 'i' to 'j',

A_1= {(i_p,j_q)}, where i_p= i_1, i_2, ..., i_p and j_q= j_1, j_2, ..., j_q (11)

Therefore, transportation cost from harvesting sites to hub or storage facilities equals

$$= \sum_{a\in\{i_p\}} I_a l_a^I H_a + \sum_{(a,b)\in A_1} C_{(a,b)} \quad (12)$$

Let, there are 'r' numbers of preprocessing plants (k) and A_2 is the set of available transportation routes towards 'k'. This set consists of transportation routes from 'j' and direct shipment routes from 'i'.

A_2= {(j_q,k_r), (i_p,k_r)},where, i_p= i_1, i_2,....., i_p ; j_q= j_1, j_2,....., j_q ; k_r= k_1, k_2,...., k_r (13)

Let, there are 's' numbers of bio-refinery plants (P) and A_3 is the set of available transportation routes towards 'P'. This set consists of transportation routes from 'k' and transshipment routes among various plants (P_s)

A_3= {(k_r,P_s),(P_x,P_y)}, Where, k_r= k_1, k_2,...., k_r ; P_s= P_1, P_2,...., P_s ; x= 1,2,...,s ; y=1,2,...,s ; $P_x \neq P_y$ (14)

Therefore, total shipment cost from harvesting sites to the bio-refinery plants passing through hub or storage facilities and preprocessing plants, along with considering direct shipments and transshipments, equals

$$= \sum_{\substack{(a,b)\in A_1 \\ (a,b)\in A_2 \\ (a,b)\in A_3}} C_{(a,b)} \quad (15)$$

Sum of the inventory costs for all of the stages equals

$$= \sum_{a\in\{i_p,j_q,k_r,P_s\}} I_a l_a^I H_a \quad (16)$$

; Where, $i_p = i_1, i_2, \ldots, i_p$; $j_q = j_1, j_2, \ldots, j_q$; $k_r = k_1, k_2, \ldots, k_r$; $P_s = P_1, P_2, \ldots, P_s$

Therefore, total transportation cost

$$= \sum_{a\in\{i_p,j_q,k_r,P_s\}} I_a l_a^I H_a + \sum_{\substack{(a,b)\in A_1 \\ (a,b)\in A_2 \\ (a,b)\in A_3}} C_{(a,b)} \quad (17)$$

$$= \sum_{a\in\{i_p,j_q,k_r,P_s\}} I_a l_a^I H_a + \sum_{\substack{(a,b)\in A_1 \\ (a,b)\in A_2 \\ (a,b)\in A_3}} \sum_{1}^{n} C_{(a,b)n} \quad (18)$$

$$= \sum_{a\in\{i_p,j_q,k_r,P_s\}} I_a l_a^I H_a + \sum_{\substack{(a,b)\in A_1 \\ (a,b)\in A_2 \\ (a,b)\in A_3}} \sum_{1}^{n} \sum_{m\in M_{(a,b)n}} \{x_{m(a,b)n} l_{(a,b)n} r_m + h_m l_{(a,b)n} + Z_{(a,b)n} f_m\} \quad (19)$$

3.2 Modeling Transportation Time

Transportation time includes shipment time and holding time. Shipment time for each mode includes travelling time and handling (e.g. loading and unloading) time. Let, t_m be the handling time per unit load for chosen mode 'm', v_m be the average travelling speed of the respective mode, then travelling time equals $x_{m(a,b)}/v_m$ and handling time equals $t_m l_{(a,b)}$. Therefore, shipment time from node 'a' to node 'b' using mode 'm',

$$= \frac{Z_{(a,b)} x_{m(a,b)}}{v_m} + t_m l_{(a,b)} \quad (20)$$

Shipment time using several modes equals

$$= \sum_{m\in M_{(a,b)}} \left\{ \frac{Z_{(a,b)} x_{m(a,b)}}{v_m} + t_m l_{(a,b)} \right\} \quad (21)$$

As mentioned before, there are several options for using single mode or some of the available modes or using all of the available modes. Let assume, $T_{(a,b)1}, T_{(a,b)2}, \ldots, T_{(a,b)n}$ are associated shipment time for various options of routes from a' to 'b'. Holding time should also be added during calculating transportation cost. In order to minimize overall required time, equation of objective function can be set as cumulative sum of times of various routes.

$$T_{(a,b)n} = \left[\sum_{m\in M_{(a,b)}} \left\{ \frac{Z_{(a,b)} x_{m(a,b)}}{v_m} + t_m l_{(a,b)} \right\} \right]_n \quad (22)$$

$$T_{(a,b)n} = \sum_{m\in M_{(a,b)n}} \left\{ \frac{Z_{(a,b)n} x_{m(a,b)n}}{v_m} + t_m l_{(a,b)n} \right\} \quad (23)$$

$$T_{(a,b)} = \sum_{1}^{n} T_{(a,b)n} \quad (24)$$

Cumulative sum of transportation times

$$= \sum_{a\in\{i_p,j_q,k_r,P_s\}} H_a + \sum_{\substack{(a,b)\in A_1 \\ (a,b)\in A_2 \\ (a,b)\in A_3}} \sum_{1}^{n} \sum_{m\in M_{(a,b)n}} \left\{ \frac{Z_{(a,b)n} x_{m(a,b)n}}{v_m} + t_m l_{(a,b)n} \right\} \quad (25)$$

3.3 Objective Functions

Two objective functions have been solved separately. The first one is minimization of transportation cost and the second one is minimization of transportation time.

Objective function 1,

$$Min\left[\sum_{a\in\{i_p,j_q,k_r,P_s\}} I_a l_a^I H_a + \sum_{\substack{(a,b)\in A_1\\(a,b)\in A_2\\(a,b)\in A_3}} \sum_{1}^{n} \sum_{m\in M_{(a,b)n}} \{x_{m(a,b)n} l_{(a,b)n} r_m + h_m l_{(a,b)n} + Z_{(a,b)n} f_m\}\right] \quad (26)$$

Objective function 2,

$$Min\left[\sum_{a\in\{i_p,j_q,k_r,P_s\}} H_a + \sum_{\substack{(a,b)\in A_1\\(a,b)\in A_2\\(a,b)\in A_3}} \sum_{1}^{n} \sum_{m\in M_{(a,b)n}} \left\{\frac{Z_{(a,b)n} x_{m(a,b)n}}{v_m} + t_m l_{(a,b)n}\right\}\right] \quad (27)$$

It is to be mentioned, that actual required time is less than the cumulative sum of time as many of the shipments run simultaneously through various routes. Actual required time equals the critical time. The critical route is the longest route from beginning stage to the end stage that requires maximum time compared to other routes. Minimization of transportation time often increases transportation cost. In case of minimization of time, if any of the alternative cost saving routes, that does not affect the critical route or does not exceed the critical time, can be chosen; the total transportation cost would be minimized. Choosing a cost saving routes after getting solution for minimization of time, will give a better solution that optimizes both transportation cost and transportation time.

3.4 Constraints

There are several constraints in biomass transportation that need to be formed. All these constraints are formed and explained in this section. If any available route (a,b)n is not using for transportation, then-

$$l_{(a,b)n} = 0 \quad (28)$$

$Z_{(a,b)n}$ is a binary variable that takes the value 1 if route (a,b)n is using for transportation.

$$Z_{(a,b)n} = \begin{cases}1, & l_{(a,b)n} > 0\\ 0, & otherwise\end{cases} \quad (29)$$

From any facility, all of the available load may not be ready for being transported immediately to the next facilities due to various reasons like unavailability of vehicles, shortage of vehicle capacity etc. Therefore, some load of biomass needed to be inventoried. Let, assume 'c_a' percent of the load is needed to be inventoried. If l_a is the available load at node 'a', l_a^I is the load to be inventoried, l_a^T is the load ready for transportation, then

$$l_a^T = l_a - l_a^I = l_a - \frac{c_a l_a}{100} = l_a(1 - 0.01c_a) \quad (30)$$

Load transferred between two nodes equals the sum of transferred load through various (parallel) options.

$$l_{(a,b)} = \sum_{n=1}^{n} l_{(a,b)n} \quad (31)$$

For node 'a', l_a^T equals the sum of the outgoing loads. It covers all the routes (a,b) that originated from 'a'. The routes (a,b) may belongs to any of the set or sets among A_1, A_2, A_3

$$l_a^T = \sum_{a:(a,b)\in A_1\cup A_2\cup A_3} l_{(a,b)} \quad (32)$$

For node 'b', sum of all incoming loads constitutes the received load l_b^r

$$l_b^r = \sum_{b:(a,b)\in A_1\cup A_2\cup A_3} l_{(a,b)} \quad (33)$$

If β is the conversion factor, then available load would be β times of received load.

$$l_a = \beta l_a^r \quad (34)$$

Received load at any node 'a' must be within the receiving capacity, Y_a of that node.

$$l_a^r \le Y_a, \text{ where } a = i_1, i_2, .., i_p, j_1, j_2, .., j_q, k_1, k_2, .., k_r, P_1, P_2, .., P_s \quad (35)$$

There should be no backflow of load between two nodes even through different routes

$$If\ l_{(a,b)} > 0;\ then\ l_{(b,a)} = 0 \quad (36)$$

Non-negativity of loads to be transferred is assumed,

$$l_{(a,b)n} \ge 0 \quad (37)$$

4. Model Verification

The biomass model developed in the previous section was verified using a hypothetical case analysis. Due to the lack of real life data in biomass transportation, a hypothetical case was developed with the help of biomass industry experts. The detail case is analyzed in the following sections.

4.1 Case Analysis

'AD Biodiesel' is the country's top class bio-refinery. It manufactures bio-diesel from yellow pine woody biomass. It follows a vertical integration of facilities but the facilities are located geographically far. There are two bio-refinery (P_1, P_2), two pre-processing plant (k_1, k_2) that supply wood pellets and there is one hub or storage facility (j_1). Fifty bags of wood pellets (each weighing 40 lb.) are tied together to form 1 ton pallet. These pallets are to be transferred from pre-processing plant to bio-refinery. AD has primarily chosen two harvesters (i_1, i_2) for consideration. The harvesters supply saw dust and other forest residues in bulk form.

The hub or storage facility is 20 miles away from i_1 and 25 miles away from i_2. The pre-processing plant k_1 is 75 miles away from both the storage facility j_1 and harvester site i_1. The distance between j_1 and k_2 is 80 miles. The Plant P_1 is 200 miles away from pre-processing plant k_1 and plant P_2 is 300 miles away from k_2. The distance between k_1 & P_2 is 400 miles, k_2 & P_1 is 250 miles. The both of the plants are 270 miles away from each other. Both of the harvesters, i_1 & i_2 have only option of using truck to transport the biomass raw material. In Hub or storage facility, material can be loaded and unloaded from truck, rail and barge. Pre-processing plant 'k_1' located beside rail station, therefore can receive as well as transfer load by using trucks and rail. Pre-processing plant k_2 located beside inland port, therefore it has option for both barge and truck. Bio-refinery plant, P_1 has option for both water and roads, P_2 are has option for roads and rails. It is to be mentioned that roads for trucking are available in all of the facilities. There are also two intermodal facilities (IM_1, IM_2) connecting roads and waterways. IM_1 is located 30 miles away from pre-processing plant k_1 and 180 miles away from refinery P_1. IM_2 is located 290 miles away from pre-processing plant k_2 and 20 miles away from plant P_2. Regarding inventory, the harvester sites store nothing. Usually, in storage facilities 20% of the available loads are inventoried, in both pre-processing and bio-refinery plants 10% of the available loads are inventoried. Harvester site i_1 is larger than the other one. In case of sufficient load, i_1 can directly ship raw material to pre-processing plant k_1 bypassing the hub. On the other hand, i_2 ship raw material to the hub only.

This case study deals with a single turnover of materials. Demand for raw material is 100 ton of wood pellet in each plant. Conversion factor of pre-processing plant is 0.75. No loss of mass can be assumed at hub or storage facility. Receiving capacity of pre-processing plant k_1 is 160 ton of bulk load and of k_2 is 140 ton of bulk load. Receiving capacity of hub or storage facility is 250 ton of bulk load. On single turnover, i_1 can provide a maximum load of 200 ton and i_2 can provide a maximum of 150 ton.

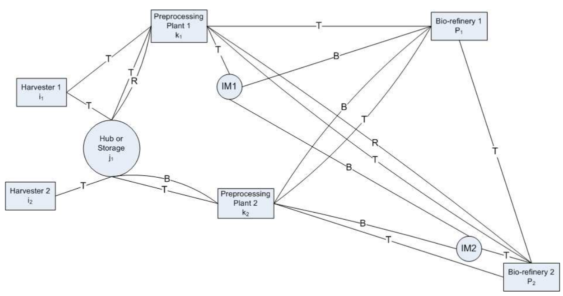

Figure 2. Transportation network of 'AD Biodiesel' mentioning available modes through the routes (T=truck, R=rail, B=barge)

4.2 Data Collection and Analysis

Units for load measurement from harvester site and storage facility to pre-processing plant = 1 ton bulk load

Units for load measurement from pre-processing plant to bio-refinery plant = 1 ton palletized load (50 numbers of bags each weighing 40 lb.)

Table 1. Inventory cost rate per unit of stored load per unit holding time

	$/ton/ hr		$/ton/ hr		$/ton/ hr		$/ton/ hr
I_{i_1}	0	I_{j_1}	0.05	I_{k_1}	0.03	I_{P_1}	0.035
I_{i_2}	0			I_{k_2}	0.03	I_{P_2}	0.035

Percentage of material inventoried, $c_{i_1} = c_{i_2} = 0$; $c_{j_1} = 0.2$; $c_{k_1} = c_{k_2} = 0.1$; $c_{P_1} = c_{P_1} = 0.1$

Table 2. Average holding time

	hour		hour		hour		hour
H_{i_1}	0	H_{j_1}	12	H_{k_1}	10	H_{P_1}	11
H_{i_2}	0			H_{k_2}	9	H_{P_2}	12

$A_1 = \{(i_1,j_1), (i_2,j_1)\}$

$A_2 = \{(j_1,k_1), (j_1,k_2), (i_1,k_1)\}$

$A_3 = \{(k_1,P_1), (k_1,P_2), (k_2,P_1), (k_2,P_2), (P_1,P_2), (P_2,P_1)\}$

Table 3. Data for various modes

Mode	Fuel cost rate, r_m	Handling cost, h_m	Fixed order setup cost, f	Average Speed, v_m	Handling time, t_m
Truck, T	0.12	1.2	100	55	0.04
Rail, R	0.06	1	200	40	0.03
Barge B	0.015	1	200	7	0.03

To transport goods from harvester or collector sites (i_1 & i_2) to hub or storage facility (j_1), only available mode is truck (T);

$M_{(i_1,j_1)1} = \{T\}, M_{(i_2,j_1)1} = \{T\},$

Only available mode for direct shipment from harvester i_1 is also truck. The hub or storage facility provides options for three modes, on the other hand k_1 provides truck and rail facility, k_2 provides option for truck and barge. Therefore, load transfer between storage facility and pre-processing plant k_1 can use either truck or rail and load transfer from storage facility to pre-processing plant k_2 can use either barge or truck.

$$M_{(i_1,k_1)1} = \{T\};\ M_{(j_1,k_1)1} = \{T\};\ M_{(j_1,k_1)2} = \{R\};\ M_{(j_1,k_2)1} = \{T\};\ M_{(j_1,k_2)2} = \{B\}$$

From k_1 to P_1, shipment can be done directly by using truck. In order to use barge, the intermodal facility, IM_1 is to be used. From k_2 to P_1, both barge and truck are available; from k_2 to P_2, beside using truck, barge can also be used by passing through the intermodal facility, IM_2; From k_1 to P_2, load can be transferred directly by using truck or rail. From k_1 to P_2, there is also an option for using barge by passing through IM_1 and IM_2.

$$M_{(k_1,P_1)1} = \{T\};\ M_{(k_1,P_1)2} = \{T,B\};\ M_{(k_2,P_1)1} = \{T\};\ M_{(k_2,P_1)2} = \{B\}; M_{(k_2,P_2)1} = \{T\};\ M_{(k_2,P_2)2} = \{B,T\};$$

$$M_{(k_1,P_2)1} = \{T\};\ M_{(k_1,P_2)2} = \{R\};\ M_{(k_1,P_2)3} = \{T,B,T\}$$

For transshipments among bio-refinery plants, available mode is truck.

$M_{(P_1,P_2)1} = \{T\};\ \ M_{(P_2,P_1)1} = \{T\},$

Table 4. Distances of various routes

routes	mile	routes	mile	routes	mile	routes	mile
$x_{T(i_1,j_1)1}$	20	$x_{T(i_1,k_1)1}$	75	$x_{T(k_1,P_1)1}$	200	$x_{T(P_1,P_2)1}$	270
$x_{T(i_2,j_1)1}$	25	$x_{T(j_1,k_1)1}$	75	$x_{T(k_1,P_1)2}$	30	$x_{T(P_2,P_1)1}$	270
		$x_{R(j_1,k_1)2}$		$x_{B(k_1,P_1)2}$	180		
		$x_{T(j_1,k_2)1}$	80	$x_{T(k_2,P_1)1}$	250		
		$x_{B(j_1,k_2)2}$		$x_{B(k_2,P_1)2}$			
				$x_{T(k_2,P_2)1}$	300		
				$x_{B(k_2,P_2)2}$	290		
				$x_{T(k_2,P_2)2}$	20		
				$x_{T(k_1,P_2)1}$	400		
				$x_{R(k_1,P_2)2}$			
				$x_{T(k_1,P_2)3}$	30		
				$x_{B(k_1,P_2)3}$	350		
				$x_{T(k_1,P_2)3}$	20		

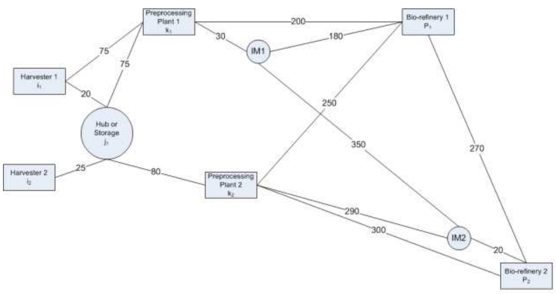

Figure 3. Distances between various facilities

$l_{P_1}^r = l_{P_1}^r = 100$

For preprocessing facility, β=0.75

For other facility, β=1

$Y_{k_1} = 160, Y_{k_2} = 140$

$Y_{j_1} = 250\ , Y_{i_1} = 200, Y_{i_2} = 150$

Transportation cost

$$\begin{aligned} = {} & l_{(i_1,j_1)1} * 4.8 + l_{(i_2,j_1)1} * 5.4 + l_{(i_1,k_1)1} \\ & * 10.2225 + l_{(j_1,k_1)1} * 10.2225 \\ & + l_{(j_1,k_1)2} * 5.5225 + l_{(j_1,k_2)1} \\ & * 10.82025 + l_{(j_1,k_2)2} * 2.22025 \\ & + l_{(k_1,P_1)1} * 25.2385 + l_{(k_1,P_1)2} \\ & * 8.5385 + l_{(k_2,P_1)1} * 31.2385 \\ & + l_{(k_2,P_1)2} * 4.7885 + l_{(k_1,P_2)1} \\ & * 49.242 + l_{(k_1,P_2)2} * 25.042 \\ & + l_{(k_1,P_2)3} * 14.692 + l_{(k_2,P_2)1} \\ & * 37.242 + l_{(k_2,P_2)2} * 8.992 \\ & + l_{(P_1,P_2)1} * 33.6035 + l_{(P_2,P_1)1} \\ & * 33.5965 \\ & + \big(Z_{(i_1,j_1)1} + Z_{(i_2,j_1)1} + Z_{(i_1,k_1)1} \\ & + Z_{(j_1,k_1)1} + Z_{(j_1,k_2)1} + Z_{(k_1,P_1)1} \\ & + Z_{(k_2,P_1)1} + Z_{(k_2,P_2)1} + Z_{(k_1,P_2)1} \\ & + Z_{(P_1,P_2)1} + Z_{(P_2,P_1)1}\big) * 100 \\ & + \big(Z_{(j_1,k_1)2} + Z_{(j_1,k_2)2} + Z_{(k_2,P_1)2} \\ & + Z_{(k_1,P_2)2}\big) * 200 \\ & + \big(Z_{(k_1,P_1)2} + Z_{(k_2,P_2)2}\big) * 300 \\ & + Z_{(k_1,P_2)3} * 400 \end{aligned}$$

Cumulative sum of transportation time

$$= 54 + 0.04 * l_{(i_1,j_1)1} + 0.04 * l_{(i_2,j_1)1} + 0.04 * l_{(i_1,k_1)1} + 0.04 * l_{(j_1,k_1)1} + 0.03 * l_{(j_1,k_1)2} + 0.04 * l_{(j_1,k_2)1} + 0.03 * l_{(j_1,k_2)2} + 0.04 * l_{(k_1,P_1)1} + 0.07 * l_{(k_1,P_1)2} + 0.04 * l_{(k_2,P_1)1} + 0.03 * l_{(k_2,P_1)2} + 0.04 * l_{(k_2,P_2)1} + 0.07 * l_{(k_2,P_2)2} + 0.04 * l_{(k_1,P_2)1} + 0.03 * l_{(k_1,P_2)2} + 0.11 * l_{(k_1,P_2)3} + 0.04 * l_{(P_1,P_2)1} + 0.04 * l_{(P_2,P_1)1} + 0.364 * Z_{(i_1,j_1)1} + 0.455 * Z_{(i_2,j_1)1} + 1.364 * Z_{(i_1,k_1)1} + 1.364 * Z_{(j_1,k_1)1} + 1.875 * Z_{(j_1,k_1)2} + 1.455 * Z_{(j_1,k_2)1} + 11.43 * Z_{(j_1,k_2)2} + 3.64 * Z_{(k_1,P_1)1} + 26.26 * Z_{(k_1,P_1)2} + 4.55 * Z_{(k_2,P_1)1} + 35.714 * Z_{(k_2,P_1)2} + 5.455 * Z_{(k_2,P_2)1} + 41.79 * Z_{(k_2,P_2)2} + 7.273 * Z_{(k_1,P_2)1} + 10 * Z_{(k_1,P_2)2} + 50.91 * Z_{(k_1,P_2)3} + 4.91 * Z_{(P_1,P_2)1} + 4.91 * Z_{(P_2,P_1)1}$$

The numbers of unit load to be transported through each of the routes are needed to be calculated with an objective of minimization of transportation cost/time subject to-

$$\left(l_{(k_1,P_2)1} + l_{(k_1,P_2)2} + l_{(k_1,P_2)3} + l_{(k_2,P_2)1} + l_{(k_2,P_2)2} + l_{(P_1,P_2)1} - l_{(P_2,P_1)1}\right) = 100$$

$$\left(l_{(k_1,P_1)1} + l_{(k_1,P_1)2} + l_{(k_2,P_1)1} + l_{(k_2,P_1)2} - l_{(P_1,P_2)1} + l_{(P_2,P_1)1}\right) = 100$$

$$\left(l_{(i_1,j_1)1} + l_{(i_2,j_1)1}\right) \le 250$$

$$\left(l_{(i_1,k_1)1} + l_{(j_1,k_1)1} + l_{(j_1,k_1)2}\right) \le 160$$

$$\left(l_{(j_1,k_2)1} + l_{(j_1,k_2)2}\right) \le 140$$

$$\left(l_{(k_1,P_1)1} + l_{(k_1,P_1)2} + l_{(k_1,P_2)1} + l_{(k_1,P_2)2} + l_{(k_1,P_2)3}\right) = 0.9 * 0.75 * \left(l_{(i_1,k_1)1} + l_{(j_1,k_1)1} + l_{(j_1,k_1)2}\right)$$

$$\left(l_{(k_2,P_1)1} + l_{(k_2,P_1)2} + l_{(k_2,P_2)1} + l_{(k_2,P_2)2}\right) = 0.9 * 0.75 * \left(l_{(j_1,k_2)1} + l_{(j_1,k_2)2}\right)$$

$$\left(l_{(j_1,k_1)1} + l_{(j_1,k_1)2} + l_{(j_1,k_2)1} + l_{(j_1,k_2)2}\right) = 0.8 * 1 * \left(l_{(i_1,j_1)1} + l_{(i_2,j_1)1}\right)$$

$$l_{(i_1,k_1)1} + l_{(i_1,j_1)1} \le 200$$

$$l_{(i_2,j_1)1} \le 150$$

Non-negativity of loads is assumed.

5. Computational Results

By using, excel solver, the optimal solution is calculated. It gives the number of unit loads to be transported through each route for minimization of time and cost separately.

Table 5: Numbers of unit loads to be transported

		Modes	For minimum cost	For minimum time	For minimum time (along with minimization of cost)
$l_{(i_1,j_1}$	$l_{(i_1,j_1)}$	$\{T\}$	43.7037	40	40
$l_{(i_2,j_1}$	$l_{(i_2,j_1)}$	$\{T\}$	131.2963	130.3704	130.3704
$l_{(i_1,k_1}$	$l_{(i_1,k_1)}$	$\{T\}$	156.2963	160	160
$l_{(j_1,k_1}$	$l_{(j_1,k_1}$	$\{T\}$	0	0	0
	$l_{(j_1,k_1}$	$\{R\}$	0	0	0
$l_{(j_1,k_2}$	$l_{(j_1,k_2}$	$\{T\}$	0	136.2963	136.2963
	$l_{(j_1,k_2}$	$\{B\}$	140	0	0
$l_{(k_1,P}$	$l_{(k_1,P_1}$	$\{T\}$	5.5	8	8
	$l_{(k_1,P_1}$	$\{T,B\}$	0	0	0
$l_{(k_2,P}$	$l_{(k_2,P_1}$	$\{T\}$	0	92	92
	$l_{(k_2,P_1}$	$\{B\}$	94.5	0	0
$l_{(k_2,P}$	$l_{(k_2,P_2}$	$\{T\}$	0	0	0
	$l_{(k_2,P_2}$	$\{B,T\}$	0	0	0
$l_{(k_1,P}$	$l_{(k_1,P_2}$	$\{T\}$	0	100	0
	$l_{(k_1,P_2}$	$\{R\}$	0	0	100
	$l_{(k_1,P_2}$	$\{T,B,T$	100	0	0
$l_{(P_1,P}$	$l_{(P_1,P_2}$	$\{T\}$	0	0	0
$l_{(P_2,P}$	$l_{(P_2,P_1}$	$\{T\}$	0	0	0
		Required cost ($)	6087.877	12906.41	10586.41
		Required time (hr)	80.879	52.8	52.8

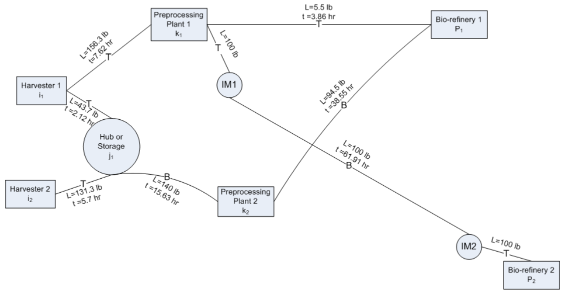

Figure 4. Transportation network for minimum cost

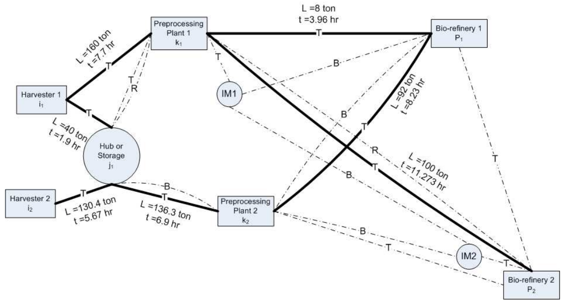

Figure 5. Transportation network for minimum time

Table 6: Transportation routes used in case of minimization of time

No.	Transportation routes	Required time (shipment time + holding time)
1	$i_1 - j_1 - k_2 - P_1$	$(1.96 + 12 + 6.9 + 9 + 8.23 + 11) = 49.09\ hr$
2	$i_2 - j_1 - k_2 - P_1$	$(5.67 + 12 + 6.9 + 9 + 8.23 + 11) = 52.8\ hr$
3	$i_1 - k_1 - P_1$	$(7.76 + 10 + 3.96 + 11) = 32.72\ hr$
4	$i_1 - k_1 - P_2$	$(7.76 + 10 + 11.273 + 12) = 41.033\ hr$

In order to minimize transportation time, fastest route between each two nodes has been chosen. Therefore, among these chosen routes, the most time consuming route can be referred as critical path. Here, The critical path is the $i_2 - j_1 - k_2 - P_1$ and critical time is 52.8 hr. Other parallel routes (e.g. 3rd, 4th) have several alternative options.

Table 7: Alternative routes

Transportation routes				Required time (shipment time + holding time)
3	$i_1 - k_1 - P_1$	a.	$i_1 - (k_1 - P_1)_1$	$(7.76 + 10 + 3.96 + 11) = 32.72\ hr < 52.8hr$
		b.	$i_1 - (k_1 - P_1)_2$	$(7.76 + 10 + 26.82 + 11) = 55.58\ hr > 52.8$hr
4	$i_1 - k_1 - P_2$	a.	$i_1 - (k_1 - P_2)_1$	$(7.76 + 10 + 11.273 + 12) = 41.033\ hr < 52.8hr$
		b.	$i_1 - (k_1 - P_2)_2$	$(7.76 + 10 + 13 + 12) = 42.76\ hr < 52.8hr$
		c.	$i_1 - (k_1 - P_2)_3$	$(7.76 + 10 + 61.91 + 12) = 91.67\ hr > 52.8hr$

In case of minimization of time, routes 3a and 4b have been used. Choosing route 4b (time=42.76 hr.) instead of 4a, will not affect the critical time (=52.8 hr.) but the total cost is reduced by 17.98% [= (12906.41-10586.41)/12906.41]. Considering other alternative routes would increase the critical time.

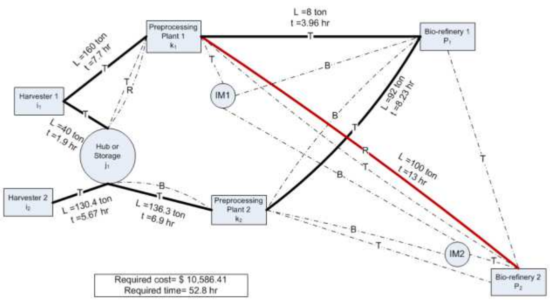

Figure 6. Modified transportation network not exceeding the critical time

Utilizing cost saving parallel routes without exceeding critical time, enables reducing total transportation cost along with satisfying the objective of minimization of time.

6. Discussion

Changing of modes through the routes may decreases variable cost (especially fuel cost) but at the same time, it increases fixed order setup cost and handling time of the transportation for same numbers of unit load. Let analyze transportation of load from K_1 to P_1. A small load (5.5 lb. or 8 lb.) is to be transported. There are two options- $(K_1,P_1)_1$ which provide transportation using only one mode, Truck; and other is the $(K_1,P_1)_2$ where mode has to be changed from truck to barge. The variable cost is lower in $(K_1,P_1)_2$ along with a high fixed order setup cost. As a result, $(K_1,P_1)_1$ become the cheaper option. Even if the numbers of unit load changed slightly, $(K_1,P_1)_1$ still remain cheaper. But in case of transportation from K_1 to P_2, where a huge numbers of unit load (100 lb.) is to be transported, the difference in variable costs overcome the difference in fixed costs. Therefore, $(K_1,P_2)_3$, which offers changing of modes twice, became cheaper than others. Moreover, the distance of (k_1,P_1) is shorter than the distance of (k_1,P_2). As changing of modes in intermodal facility often introduces extra handling cost and time, which has to be recovered by saving cost and time for the rest of the routes. Therefore, it can be concluded based upon cost factor, changing of modes is more appropriate for long distance transportation of larger load.

Transportation time for a mode is proportional to the speed of the mode and handling time. In the case study, the differences in speeds of various modes are larger than the differences in handling times of various modes. Practically, speeds of modes do not depend on quantity of loads but handling time is proportional to the quantity of loads. Therefore, in case of comparing transportation times, choosing of modes is not significantly affected by the quantity of loads. In case of availability of several modes, if using more than one mode increases average speed of the route, then it is appreciable; otherwise, it will affect adversely due to increased handling time.

7. Conclusion

This research provides three types of solution. In order to minimize the transportation cost, cheapest modes of transportation have been selected in each route. Simultaneously, it requires more time. With an objective of minimization of time, the fastest mode of transportations has been chosen in each of the route. Fastest modes often induce extra cost. Therefore, it refers to a costly solution. It is noticed that, there are many routes having slack time for transportation. That means, fast transportation through some routes do not add value to the network rather adding extra cost. This happens due to availability of some parallel routes and some precedent routes. Succeeding transportation from some nodes/facilities can't be started unless all of precedent transportations had been finished. In such cases, cost saving modes can be chosen through some of the routes unless required time does not exceed the time of the parallel routes. Such careful choice of mode through various routes would minimize both of the transportation time and the transportation cost.

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