Ant Colony Optimization for Road Modifications

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Abstract

Non-conventional products provide opportunities for the forest industry to increase economic value from forests; however, these products may require specialized or non-standard vehicles to transport these products. The existing forest transportation network was not necessarily designed to the road standards required for these non-standard vehicles. Several options are available to forest managers to allow these vehicles to navigate the forest transportation network including filling the ditch, removing the superelevation, reversing the superelevation, or even reconstructing the roadway. For each investment, there is an associated vehicle that can traverse the road segment if the investment is made. This paper uses the ant colony heuristic to identify the optimal vehicle choice and road modification option to effectively transport non-conventional products.

Keywords: Ant Colony Optimization, Biomass Transport, Vehicle Accessibility

Introduction

The production of high valued non-conventional products, such as utility poles or the production of low valued products such as chips or hogfuel, provide opportunities for the forestry industry to increase economic value from forests. However, most of the forest transportation system has been designed and built for long-log, stinger-steered trailers (Sessions et al., 2010) and there is little engineering record of road design or location throughout the forest industry (Craven et al., 2011). For example the 15,000 acre OSU College Forests and the 70,000 acre Starker Forests have no data on the horizontal, vertical, or cross-sections of their roads (Lysne and Klumph, 2011; Beathe, 2011). This lack of engineering records provides a challenging environment in the assessment for transporting non-conventional products. The primary challenge to hauling non-conventional products, on non-standard vehicles, is determining if the vehicle can navigate the horizontal and vertical geometry unloaded and loaded, as well as turning around near the landing. These non-standard vehicles include pole trailers with rear self-steering axles, pole trailers with stinger-steered axles, fifth-wheel chip vans (with and without self-steering rear axles), and stinger-steered chip vans. We define a pole trailer as a stinger-steered trailer with a bunk-to-bunk distance longer than 28 feet, hauling logs that are longer than 45 feet.

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Problem Description

Several choices affect the accessibility of these non-standard vehicles. These choices include temporarily filling the ditch, removing or reversing the superelevation to reduce lateral tire slip, and widening the roadway. During the dry months, temporarily filling the ditches or changing the superelevation of the roadway are options that permit non-standard vehicles access. Temporarily filling the ditch provides a greater road width for the non-standard vehicle to pass, usually two to five feet of extra road width. Superelevation of the road surface is constructed into forest roads to drain water from the road surface. During the dry months, superelevation is not needed; providing an opportunity to alter the superelevation to reduce lateral tire slip toward the inside of a curve. Two options exist when altering the superelevation (1) remove the superelevation and (2) reverse the superelevation. Removing the superelevation reduces the amount of off-tracking that a vehicle produces by reducing the amount of lateral tire slip due to gravity. Reversing the superelevation could be used to counteract off-tracking; allowing the weight of the vehicle and the effects of gravity on an inclined plane to counter the effects of off-tracking. Lastly, forest engineers and managers can affect the outcome by redesigning the roadway to allow these vehicles access along the entire length. This is achieved by widening the roadway and removing obstacles close to the roadway such as standing trees.

Each modification option has an associated cost and benefit. For example, if a 45-ft drop center 5^{th}-wheel chip van needs an extra 2 feet of road width to access a harvest unit, the ditches might be temporarily filled to allow the 5^{th}-wheel chip van access. If the ditches were not filled, the only vehicle that might have access to the unit would be a stinger-steered chip trailer. Not only does the amount of off-tracking vary between vehicles, so does the volume of chips or hogfuel consistent with weight restrictions that these vehicles can haul. The operating cost and traveling speed vary for each vehicle configuration, creating a multi-dimensional problem. Mixed integer linear programming can be used to solve the underlying mathematical problem for small problems. As an alternative solution method, this paper looks at the use of Ant Colony Optimization (ACO) to determine the optimal vehicle type, path, and road modifications for transporting biomass.

Mathematical Formulation

The mathematical problem is to minimize the sum of road modifications and biomass transportation costs. Let G=(N,A) be a directed network with nodes N and arcs (i,j) within A. We associate with each node i within N a number S(i) which indicates the supply or demand depending on whether S(i) > 0 or S(i) < 0. The minimal cost problem is then

Minimize

$$\sum_{(i,j)\in A} FC_{ij}^{t} * Y_{ij}^{t} + \sum_{(i,j)\in A}\sum_{t\in T} VC_{ij}^{t} * Volume_{ij}^{t} \quad \forall\ (i,j)\in A, t\in T \qquad (1)$$

Conservation of Flow

$$\sum_{\{ji(i,j)\in A\}} Volume_{ij}^{t} - \sum_{\{ji(j,i)\in A\}} Volume_{ji}^{t} = V^{t}(i) \quad \forall\, i \in N \tag{2}$$

Sale Volumes

$$\sum_{t\in T} V^{t}(i) = S(i) \qquad \forall\; i \in N \tag{3}$$

Road Triggers

$$\sum_{t\in T} M * Y_{ij}^{t} \geq Volume_{ij}^{1} \qquad \forall\,(i,j)\in A \tag{4}$$

$$\sum_{t\in T\,(t\geq 2)} M * Y_{ij}^{t} \geq Volume_{ij}^{2} \qquad \forall\,(i,j)\in A \tag{5}$$

$$\sum_{t\in T\,(t=3)} M * Y_{ij}^{t} \geq Volume_{ij}^{3} \qquad \forall\,(i,j)\in A \tag{6}$$

Decision Variables

$$Y_{ij}^{t} = \{0,1\} \qquad \forall\,(i,j)\in A, t\in T \tag{7}$$

$$Volume_{ij}^{t} \geq 0 \qquad \forall\,(i,j)\in A, t\in T \tag{8}$$

Equation (1) is the objective function. FC_{ij}^{t} is the fixed cost to modify link *ij* to allow truck type *t* access. Y_{ij}^{t} is a binary variable, zero if the link is not used, and one if the link is used. VC_{ij}^{t} is the variable cost over link *ij* in truck type *t,* (\$/ton). $Volume_{ij}^{t}$ is the amount of volume crossing link *ij* in truck type *t,* (tons). Equation (2) provides conservation of flow at each node for each truck type. $V^{t}(i)$ is the volume entering each node *i* for each truck type *t,* (tons). Equation (3) requires that the total supply or demand at each node $S(i)$ (tons), equal the sum of the volume transported over all truck types. Equation (4) requires that the road modification for truck type *1* (the lowest standard truck type) be made to at least pass truck type *1* if there is volume passing over link *ij* in truck type *1*. Equation (5) requires that the road modification for truck type *2* (the moderate standard truck type) be made to at least pass truck type *2* if there is volume passing over link *ij* in truck type *2.* Equation (6) requires that the road modification for truck type *3* (the highest standard truck type) be made to pass truck type *3* if there is volume passing over link *ij* in truck type *3.* Equation (7) requires that the road trigger for link *ij* for truck type *t* be a binary variable, zero or one. Equation (8) requires that the volume passing over link *ij* for truck type *t* be equal to or greater than zero.

Review of Ant Colony Optimization

The ACO (Dorigo and Stuzle, 2004) is based on the analogy of ants searching for food. Ants randomly walk in search of food leaving a pheromone behind as they travel. The pheromone is a scent that influences other ants to take that path. As more ants travel over the same path the pheromone increases, increasing the possibility of an ant choosing that path. This process continues until all ants are following the same path to the food source. The ACO heuristic has been used to solve fixed cost and variable cost forest transportation problems with side constraints (Contreras, Chung, and Jones, 2008; Sessions, 1985). Outside of the forest industry, this heuristic has been used to solve vehicle route scheduling problems, capacitated vehicle routing problems, and scheduling problems (Donati et al. 2008; Rizzoli et al., 2007).

Ant Colony Optimization

The ACO developed in this paper is designed to minimize the total transportation cost. The total transportation cost is the sum of the modifications costs plus the variable costs multiplied by the volume of each harvest unit. If a truck is loaded at sale *x*, it must make it to destination *z* using the same truck. If different types of trucks use the same link, the one with the maximum fixed cost will be applied. Therefore, if road modifications are applied so that a 53-ft drop center 5th-wheel chip van can navigate the road, no other modifications need to take place for other truck types. The ACO regards each road modification option as a separate link. In other words, between each node three links exist; one that has no fixed cost, one that has a moderate fixed cost, and one that has a large fixed cost; all of which end up at the same node (Figure 1). As the algorithm progresses through each set of ants, each ant in each set has a designated modification option that it will choose from as it progresses through the network. It was chosen to have three kinds of ants; a truck type *1* ant, a truck type *2* ant, and a truck type *3* ant to diversify the search. With this formulation, each modification option has its own set of pheromones. The starting pheromones provided an equal probability choosing each link leaving a node for each truck type. As the algorithm identifies a lower total cost route from each sale, the links that are not part of that path have their pheromones decay. We use a constant decay factor of 25 percent.

The ACO was compared to a mixed integer linear programming model, using a small network (Figure 1). The large black circles are the nodes in the network. The small black circles are the road modification option for the 53-ft drop center 5th-wheel chip van, the small horizontally hatched circles are the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles are the no road modification option for the stinger-steered chip van. In this formulation, three different degrees of road modification could be applied, no modification, moderate modification, or severe modification. The no modification option will only allow a stinger-steered chip van access. The moderate modification option will allow a stinger-steered chip van and a 45-ft drop center 5th-wheel chip van access. The severe modification will allow all three trucks access to the road segment. Each truck has a different hourly operating cost. The stinger-steered chip van has an estimated hourly cost is $95.37, the 45-ft drop center 5th-wheel chip van hourly cost is $90.95, and the 53-ft drop center 5th-wheel chip van hourly cost is $99.79 (Table 1). We assumed cost per hour did not vary with speed or road type.

The modification costs vary on the severity of the required modifications. The moderate modification option was assumed to require removing the superelevation within the roadway and filling the ditches to allow the 45-ft drop center 5th-wheel chip van access. We assumed that these modifications would cost $100 per station for half of the length of the link. The severe modification option was assumed to require filling the ditches, reversing the superelevation, and widening the roadway on a few select curves. These modifications were estimated to cost $300 per station for half of the length of the link (Table 1). We assumed that only half of the segment length needed to be modified because on a forest road (using a conservative estimate) curves are approximately half of the transportation network.

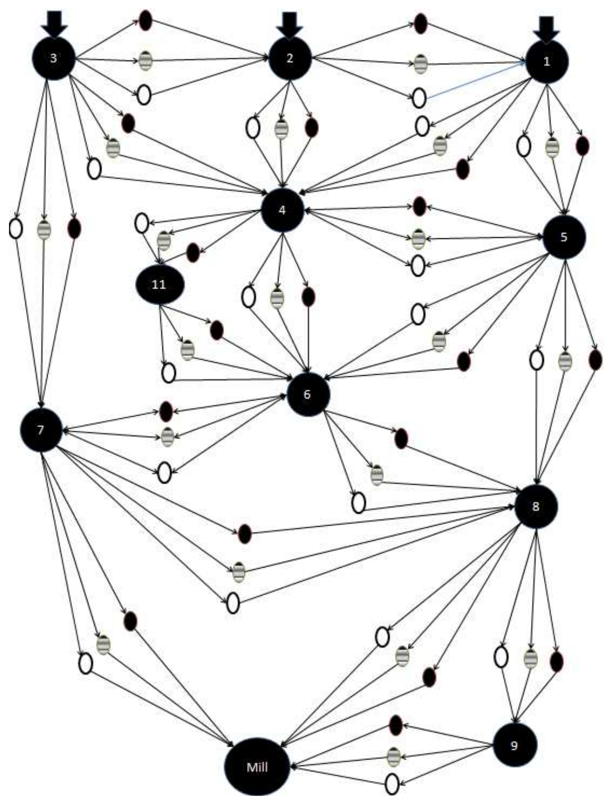

Figure 1. Small example road modification network, adapted from (Sessions 1985).

The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 53-ft drop center 5th-wheel chip van, small horizontally hatched circles indicate the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

Table 1. Chip Van Operating Characteristics.

Trailers	Volume Capacity cubic feet	Stations per Hour on Forest Roads	Stations per Hour on Highways	Operating Cost $/hr	Modification Cost $/Station
42' Stinger	2,600	528	2,376	$95.37	$0
45' Drop Center 5th-wheel	3,300	528	2,376	$90.95	$100
53' Drop Center 5th-wheel	4,000	528	2,376	$99.79	$300

The sale nodes for the small network are nodes 1, 2, and 3. The associated amount of biomass for each sale (chips or hogfuel) is identified in Table 2. All of the biomass is to be delivered to only one Mill (Node 10). The haul and modification costs per link are provided in the appendix (Table 5).

Table 2. Sale Nodes

Volume of Biomass		
Harvest Node	**Destination Node**	**Biomass (million ft^3)**
1	10	4.8
2	10	1.02
3	10	6.2

The ACO had a stopping criterion of 1,000 iterations. The heuristic converged on its solution rather quickly (iteration 282). The optimal solution to this problem using the ACO is $72,139.50. This amounted to $6,225 in modification costs and $65,914.50 in hauling costs. The optimal path is shown for each sale in Table 3. There were 1,454 trips from Unit 1 to the Mill, 309 trips from Unit 2 to the Mill, from and 1,550 trips from Unit 3 to the Mill.

Table 3. The Optimal Path for the Small Network Using Ant Colony Heuristic.

Total Cost	$72,139.50	
Sale 1	**Sale 2**	**Sale 3**
Truck Type	**Truck Type**	**Truck Type**
45' Drop Center 5th-wheel	45' Drop Center 5th-wheel	53' Drop Center 5th-wheel
Best Node Path	**Best Node Path**	**Best Node Path**
1	2	3
5	4	7
6	11	10
7	6	
10	7	
	10	

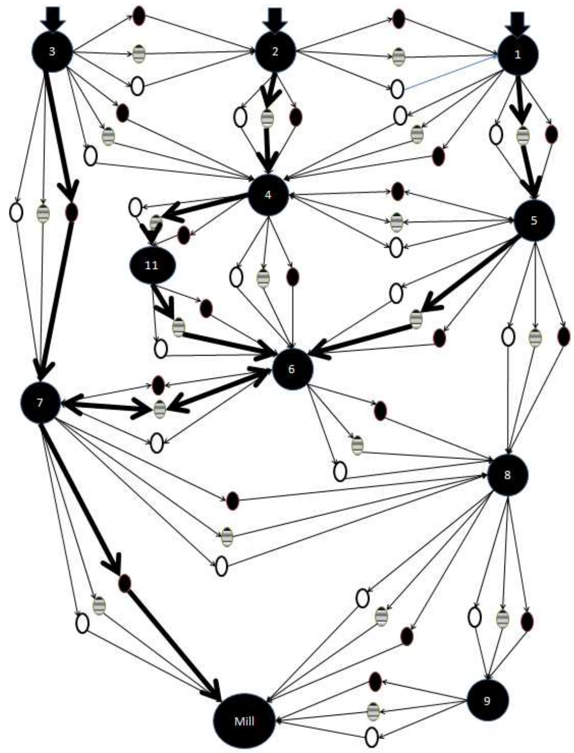

Figure 2. Ant Colony Optimal Haul Routes.

The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 53-ft drop center 5th-wheel chip van, the small horizontally hatched circles indicate the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

The ACO solution was compared to a mixed integer solution. The mixed integer programming solution is found in Table 4 and Figure 3. The mixed integer and ACO produced similar results; a $13.46 difference between the two approaches. This was the result of rounding when formulating the mixed integer problem. Both methods used the same truck types and paths to transport the biomass to the mill. This small example illustrates that the heuristic appears reasonable for determining near optimal solutions for similar road modification problems.

Table 4. The Optimal Path for the Small Network Using Mixed Integer Programming.

Total Cost	$72,154.26	
Sale 1	**Sale 2**	**Sale 3**
Truck Type	**Truck Type**	**Truck Type**
45' Drop Center 5th-wheel	45' Drop Center 5th-wheel	53' Drop Center 5th-wheel
Best Node Path	**Best Node Path**	**Best Node Path**
1	2	3

5	4	7
6	11	10
7	6	
10	7	
	10	

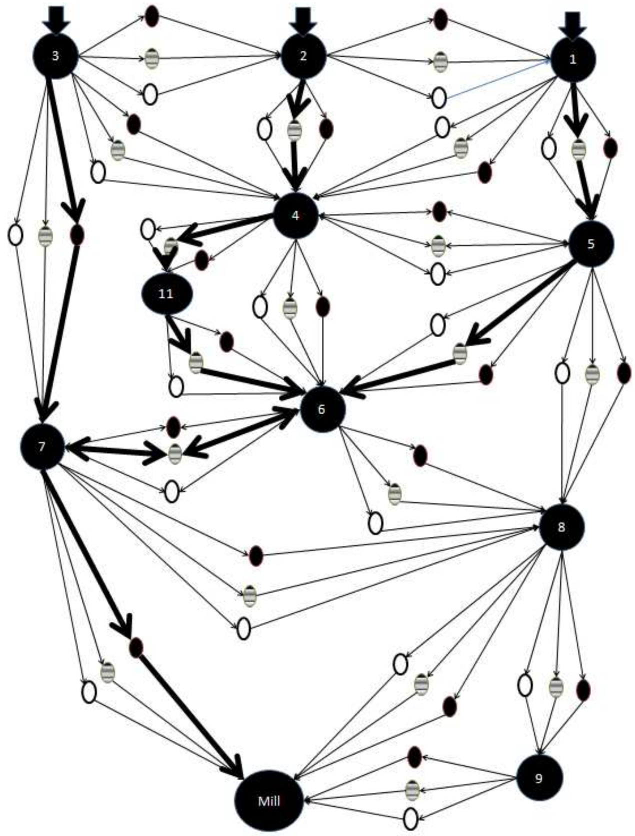

Figure 3. Mixed Integer Optimal Haul Routes.

The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 53-ft drop center 5th-wheel chip van, small horizontally hatched circles indicate the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

Application to a realistic forest transportation network

Following the favorable results of the small network, the ACO heuristic was used on the McDonald Forest, to determine the least cost path for future harvesting activities. McDonald Forest is located seven miles north of Corvallis and is managed by Research Forest staff, College of Forestry, Oregon State University. McDonald Forest is a teaching, research and demonstration forest revolving around four themes. These themes are 1) Short Rotation Wood Production with High Return on Investment, 2) High

Quality, Growth Maximizing Timber Production, 3) Visually Sensitive, Even-aged Forest, and 4) Structurally Diverse Forest (Fletcher, et al., 2005).

Biomass utilization is gaining interest in western Oregon and several biomass-powered cogeneration plants exist within 60 miles of McDonald Forest. A major cost of biomass operations is the transportation cost and with small profit margins, thus it is important to determine the least cost method for transporting biomass from the woods to the mill. Being able to determine the optimal trucks and haul routes that would reduce total transportation costs would be important to the decision to utilize biomass. We applied the ACO heuristic to develop a least cost path from a sample of harvest units distributed through McDonald Forest. McDonald Forest is approximately 7,200 acres with 70 miles of road or about 6 miles of forest roads per square mile (Lysne and Klumph, 2011). The McDonald Forest road network and possible truck routes through Corvallis are shown in Figure 3.

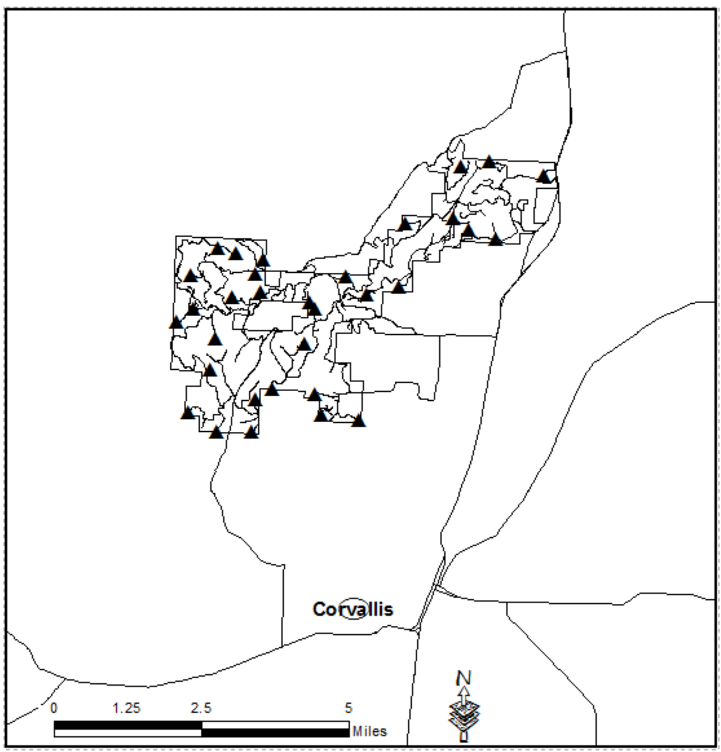

Figure 4. McDonald Forest Road Network, Corvallis, Oregon. The black triangles are the sale nodes.

Thirty hypothetical timber harvests (sales) were spread through McDonald Forest (Figure 3) for the purpose of reducing fuel loading around the urban interface. These timber harvests were assumed to produce and recover 40 green tons of biomass per acre or 4,000 ft^3 of biomass with about 50 percent moisture content. It was estimated that each sale would harvest between 120 and 240 acres (black triangles in Figure 3). The destination node for all of the transported biomass is a biomass plant in Eugene (30 miles south of Corvallis). The estimated travel speed on forest roads was 10 mph and

45 mph on major highways. On public highways, it was assumed that any truck combination could be used without incurring any road modification costs.

The transportation network included 405 nodes and 2,433 links, including the existing transportation network and two modification options for each link. The existing transportation network was assumed to only permit stinger-steered trailer access. The other two trailer types required temporary road modification for access similar to the small network problem. The chip van operating characteristics in this problem are the same as Table 1. Once the chip vans were outside of the McDonald Forest, it was assumed that any chip van could be used without incurring a road modification cost. It was also assumed that adequate turnarounds exist to permit use of each truck type.

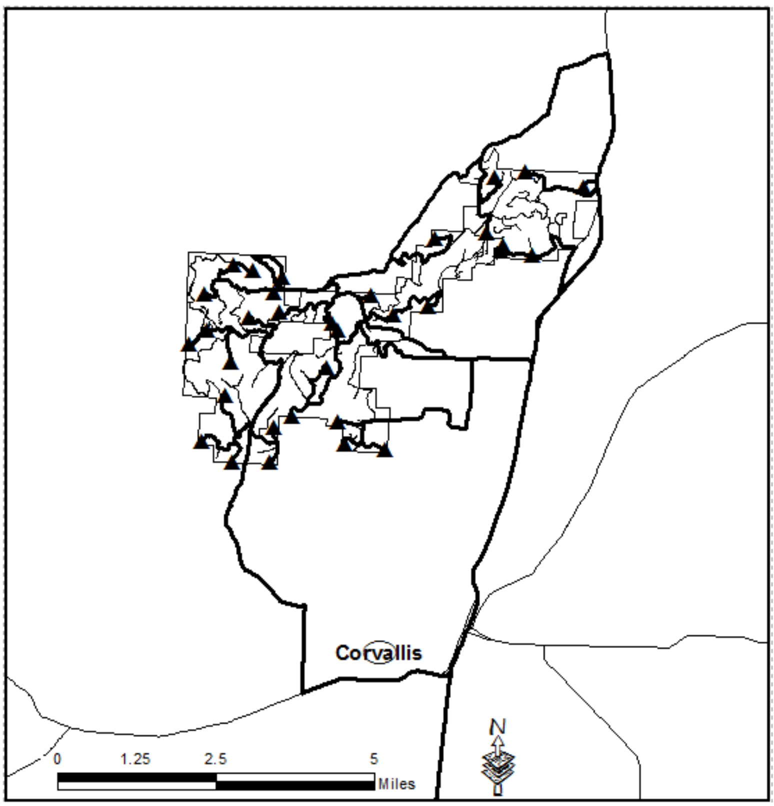

Figure 5. Optimal route path for all 30 sales, McDonald Forest, Corvallis, Oregon.

The bold routes are the optimal paths. The black triangles are the sale nodes.
The optimal routes for the 30 sales are shown in Figure 5. For 29 sales, the ACO determined the least cost path used a 53-ft drop center 5^{th}-wheel chip van and for one sale, a 45-ft drop center 5^{th}-wheel chip van was chosen. The total transportation cost was $1,491,020 with $219,820 in road modification costs and $1,271,200 in haul costs. The road modification costs amount to fifteen percent of the total cost. If no road modifications had been made, only the stinger steered chip van could have been used with a total transportation cost of $1,815,650 (100 percent haul costs). In this example, the ability to modify the roadway to allow larger trucks access to these sales reduced the total transportation cost by 22 percent. The ability to reduce transportation costs by 22 percent is a large benefit when margins are as slim as they are in the biomass

market. This implies that being able to reduce the haul cost with the application of road modifications could have a significant positive impact.

Concluding Comments

The ACO heuristic obtained an optimal solution to a small problem and when applied to a more realistic problem provided a solution quickly. As the amount of volume being transported increases, the more a company could spend on road modifications to allow larger truck capacity access. Being able to change the forest transportation network to allow larger truck access could dramatically reduce hauling costs. Further research is required to determine if the associated costs used in this paper accurately represent the road modification costs required to allow these non-standard trucks access. Further research is also required to determine the effect of superelevation has on the magnitude of non-standard truck off-tracking on forest roads.

Literature Cited

Beathe, J. 2011. Starker Forests' Road Inventory. Beck, S. Interviewer. Corvallis, Oregon.

Contreras, M. A., Chung, W., and Jones, G. 2008. Applying Ant Colony Optimization Metaheuristic to Solve Forest Transportation Planning Problems with Side Constraints. Canadian Journal of Forest Research, 38, 2896-2910.

Craven, M., Wing, M., Session, J., and Wimer, J. 2011. Assessment of Airborne Light Detection and Ranging (LiDAR) for use in Common Forest Engineering Geomatic Applications. M.S. Thesis, Oregon State Universtiy, College of Forestry, Corvallis. Retrieved from Oregon State University: http://hdl.handle.net/1957/21803

Donati, A. V., Montemanni, R., Casagrande, N., Rizzoli, A. E., and Gambardella, L. M. 2008. Time Dependent Vehicle Routing Problem with a Multi Ant Colony System. European Journal of Operational Research, 185, 1174-1191.

Fletcher, R., Johnson, B., Blanchard, G., Hayes, J., Johnson, N., Johnson, D., Lysne, D., Murphy, G., Newton, M.; Sessions, J. 2005. McDonald-Dunn Forest Plan. Last Accessed May 5, 2012, from http://www.cof.orst.edu/cf/forests/mcdonald/plan/files/mcdunn_plan.pdf

Lysne, D., and Klumph, B. 2011. OSU College Forests' Road Inventory. Beck, S. Interviewer. Corvallis, Oregon.

Rizzoli, A. E., Montemanni, R., Lucibello, E., and Gambardella, L. M. 2007. Ant colony Optimization for Real-World Vehicle Routing Problems: From Theory to Applications. Swarm Intelligence, 1, 135-151.

Sessions, J. 1985. A Heuristic Algorithm for the Solution of the Variable and Fixed Cost Transportation Problem. Society of American Foresters Symposium p. 324-336. Athens, Georgia: Georgia Center for Continuing Education.

Sessions, J., Wimer, J., Costales, F., and Wing, M. G. 2010. Engineering Considerations in Road Assessment for Biomass Operations in Steep Terrain. Western Journal of Applied Forestry, 25(3), 144-153.

Table 5. Haul and Modification Cost for the Small Network

Link Identifier		Truck Type	Round Trip Haul Cost $/Truck/Link	Modification Cost $/Link
From	To			
1	4	42' Stinger	18.79	0
1	4	45' Drop Center 5^{th}-wheel	17.91	2,600.00
1	4	53' Drop Center 5^{th}-wheel	19.66	7,800.00
1	5	42' Stinger	6.14	0
1	5	45' Drop Center 5^{th}-wheel	5.86	850
1	5	53' Drop Center 5^{th}-wheel	6.43	2,550.00
2	1	42' Stinger	12.28	0
2	1	45' Drop Center 5^{th}-wheel	11.71	1,700.00
2	1	53' Drop Center 5^{th}-wheel	12.85	5,100.00
2	4	42' Stinger	6.14	0
2	4	45' Drop Center 5^{th}-wheel	5.86	850
2	4	53' Drop Center 5^{th}-wheel	6.43	2,550.00
3	2	42' Stinger	9.39	0
3	2	45' Drop Center 5^{th}-wheel	8.96	1,300.00
3	2	53' Drop Center 5^{th}-wheel	9.83	3,900.00
3	4	42' Stinger	6.5	0
3	4	45' Drop Center 5^{th}-wheel	6.2	900
3	4	53' Drop Center 5^{th}-wheel	6.8	2,700.00
3	7	42' Stinger	6.32	0
3	7	45' Drop Center 5^{th}-wheel	6.03	875
3	7	53' Drop Center 5^{th}-wheel	6.61	2,625.00
4	5	42' Stinger	9.03	0
4	5	45' Drop Center 5^{th}-wheel	8.61	1,250.00
4	5	53' Drop Center 5^{th}-wheel	9.45	3,750.00
4	6	42' Stinger	6.14	0
4	6	45' Drop Center 5^{th}-wheel	5.86	850
4	6	53' Drop Center 5^{th}-wheel	6.43	2,550.00
4	11	42' Stinger	4.34	0
4	11	45' Drop Center 5^{th}-wheel	4.13	600
4	11	53' Drop Center 5^{th}-wheel	4.54	1,800.00
5	4	42' Stinger	7.95	0
5	4	45' Drop Center 5^{th}-wheel	7.58	1,100.00
5	4	53' Drop Center 5^{th}-wheel	8.32	3,300.00
5	6	42' Stinger	3.61	0

Link Identifier		Truck Type	Round Trip Haul Cost $/Truck/Link	Modification Cost $/Link
From	To			
5	6	45' Drop Center 5th-wheel	3.45	500
5	6	53' Drop Center 5th-wheel	3.78	1,500.00
5	8	42' Stinger	6.14	0
5	8	45' Drop Center 5th-wheel	5.86	850
5	8	53' Drop Center 5th-wheel	6.43	2,550.00
6	7	42' Stinger	5.42	0
6	7	45' Drop Center 5th-wheel	5.17	750
6	7	53' Drop Center 5th-wheel	5.67	2,250.00
6	8	42' Stinger	6.5	0
6	8	45' Drop Center 5th-wheel	6.2	900
6	8	53' Drop Center 5th-wheel	6.8	2,700.00
7	6	42' Stinger	1.81	0
7	6	45' Drop Center 5th-wheel	1.72	250
7	6	53' Drop Center 5th-wheel	1.89	750
7	8	42' Stinger	6.5	0
7	8	45' Drop Center 5th-wheel	6.2	900
7	8	53' Drop Center 5th-wheel	6.8	2,700.00
7	10	42' Stinger	9.03	0
7	10	45' Drop Center 5th-wheel	8.61	0
7	10	53' Drop Center 5th-wheel	9.45	0
8	9	42' Stinger	5.06	0
8	9	45' Drop Center 5th-wheel	4.82	700
8	9	53' Drop Center 5th-wheel	5.29	2,100.00
8	10	42' Stinger	19.51	0
8	10	45' Drop Center 5th-wheel	18.6	0
8	10	53' Drop Center 5th-wheel	20.41	0
9	10	42' Stinger	9.03	0
9	10	45' Drop Center 5th-wheel	8.61	0
9	10	53' Drop Center 5th-wheel	9.45	0
11	6	42' Stinger	0.36	0
11	6	45' Drop Center 5th-wheel	0.34	50
11	6	53' Drop Center 5th-wheel	0.38	150