LOGISTICS OF INTEGRATING A BIOMASS CONVERSION TECHNOLOGY INTO A CENTRALIZED BIOMASS RECOVERY OPERATION SUPPLY CHAIN

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ABSTRACT

LOGISTICS OF INTEGRATING A BIOMASS CONVERSION TECHNOLOGY INTO A CENTRALIZED BIOMASS RECOVERY OPERATION SUPPLY CHAIN

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Appropriate pre-treatment steps coupled with the production of advanced biofuels such as biochar or torrefied wood chips within a supply chain can ease the economic transportation limitations of a biomass recovery operation. Potential benefits include local energy independence from fossil fuels as well as newly accessible international markets for advanced feedstocks. The objectives of this study were to examine the logistic effects of integrating a BCT into a Centralized Biomass Recovery Operation (CBRO). Concurrently, this study examined two different CBRO workflows/supply chains in order to facilitate integration into a variety of supply chains. Centralized pre-treatment and conversion sites range from 0.22 acres to 3.57 acres of land available. This study used the Location-Allocation tool within the Network Analyst extension to generate total and average one-way travel times for analysis of each model. The models used the Maximize Market Share problem type. A sensitivity analysis was conducted in order to explore the effect that having multiple BCT sites has on the total and average one-way travel time of either model. System balance was determined for all iterations of both logistics models which all scenarios within a given Logistics model exhibited shorter travel times than the other. Logistically, arranging comminution and BCT

operations to occur at the same in-woods site returned shorter total and average travel times than arranging the two activities to occur at separate in-woods sites.

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TABLE OF CONTENTS

LIST OF TABLES

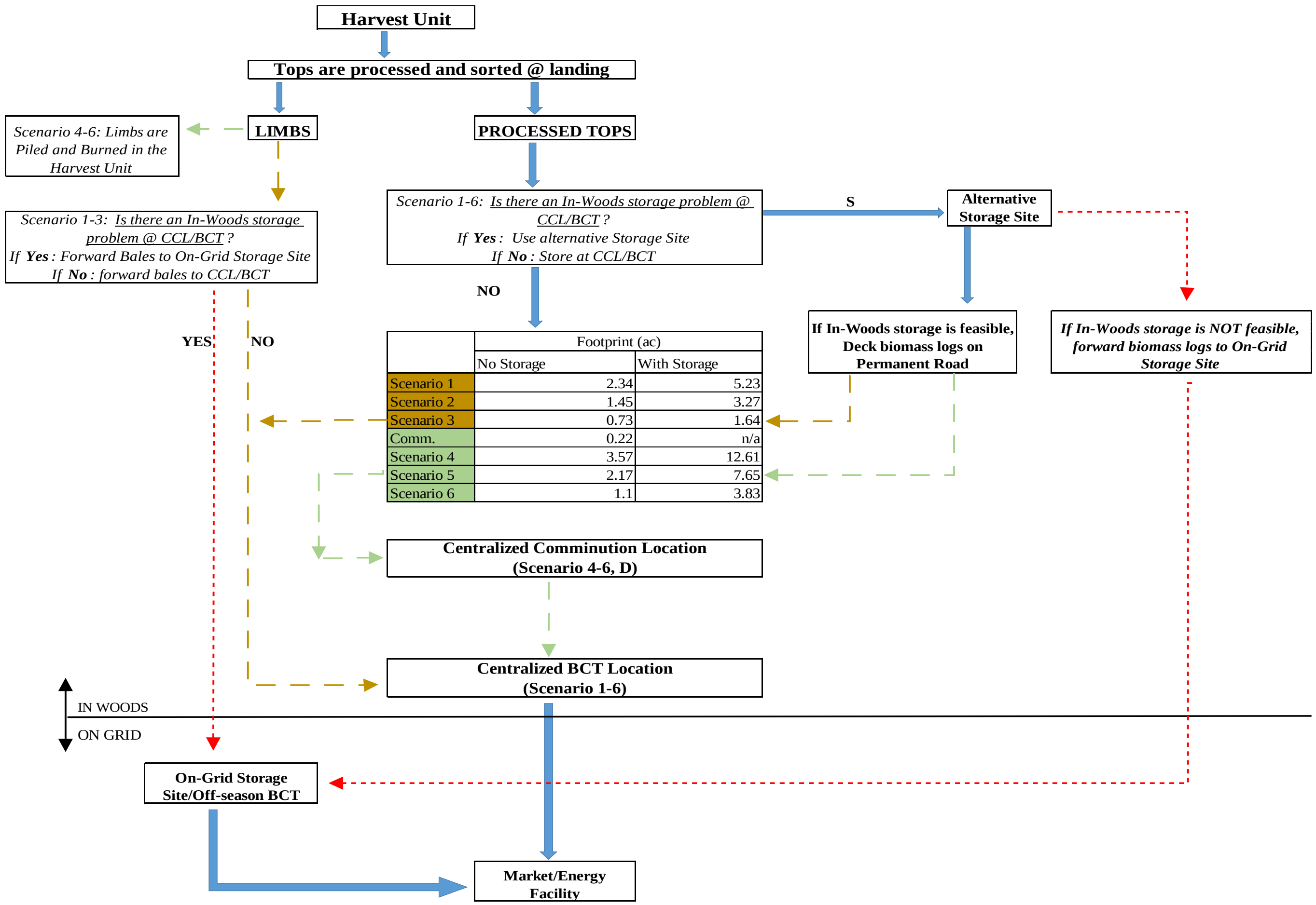
LIST OF FIGURES

LIST OF APPENDICES

INTRODUCTION

Humboldt County has great potential to develop sustainable and renewable energy programs due to the large acreage of Timber Production Zone (TPZ) property in combination with emerging Biomass Conversion Technologies (BCT). If successful, other rural counties may be able to integrate similar models and realize energy independence. In order to determine if integrating a BCT into a Centralized Biomass Recovery Operation (CBRO) is feasible, a suitability analysis needs to be conducted to identify the candidate sites for comminution and conversion. Furthermore, a network analysis will need to be conducted to determine both total and average one-way hauling time. Utilizing innovative harvest systems, there is potential in Humboldt County to supply bioenergy facilities that would power the entire county on renewable energy, but the biomass required is largely inaccessible due to economic transportation limitations. With appropriate pre-treatment steps coupled with properly located conversion equipment, and the production of advanced biofuels such as biochar or torrefied wood chips, the economic transportation limitations of a biomass recovery operation may be improved. Potential benefits include local energy independence from fossil fuels as well as newly accessible international markets for converted feedstocks.

Although organizing a CBRO that supports a BCT may seem quite difficult (Figure 1), there are many economic, ecological, and social benefits to potentially be realized. First, there will be many jobs created as a result of additional biomass recovery operations. There will potentially be additional loggers, equipment operators, mechanics, truck drivers, engineers, and energy facility personnel to account for the additional volume of material being handled. Rural supplier counties are expected to experience economic growth as a result of domestic and international sales of converted forest residues. With the utilization of intermodal transport, international markets can be accessed. Humboldt County, along with many other rural timber producing countries, will potentially be able to achieve energy independence as well as reduce the dependence on unsustainable fossil fuels such as natural gas, coal, or oil. Other potential benefits of utilizing the forest residues in such a manner is more fire resistant forests as well as ease of post-harvest treatments.



	Footprint (ac)	
	No Storage	With Storage
Scenario 1	2.34	5.23
Scenario 2	1.45	3.27
Scenario 3	0.73	1.64
Comm.	0.22	n/a
Scenario 4	3.57	12.61
Scenario 5	2.17	7.65
Scenario 6	1.1	3.83

Figure 1- A decision making flow chart that can be used for organizing workflow of a CBRO.

1.1- What Is Biomass And How Much Of It Do We Have?

There are many different forms of sustainable and renewable energy sources available to us today. Among the different forms of renewable sources, biomass plays an important role, thanks to its homogenous and wide distribution across the world (Frombo et al., 2009). Over the past two decades, biomass energy has emerged as the most successful alternative to the use of fossil fuels (Noon and Daly, 1996); however, due to high costs and low product value, the economy of forest biomass procurement is critical (Windisch, 2015). Consequently, in order to understand the future of bioenergy, it is important to analyze the biomass resources that can be potentially useful for energy conversion (Frombo et al., 2009).

Timber harvest operations typically generate a waste product, commonly referred to as “biomass”, “harvest residues”, or “slash”. Biomass can be defined as commercially low value materials such as tree tops, limbs, chunks, small diameter, and non-merchantable trees which are a result of timber harvest or thinning operations (Harrill and Han, 2010). Approximately 41 million dry tons of biomass is produced yearly in the Western United States (Perlack et al., 2005). The annual biomass available in California is estimated at 24 million dry tons, of this, only 13 million metric dry tons are accessible by way of permanent roads (Han et al., 2010). Humboldt County has a tremendous woody biomass resource that is already used to meet 25%-35% of local electricity demands with potential to expand this use of biomass for energy production (Marshall and Zoellick, 2012).

The preferred type of application for this study is the rural area because of the reasonable relation between the potential of biomass and the transportation distances that have a great influence on the economic viability (Nagel, 2000). As such, there is great potential for the increased utilization of forest residues in Humboldt County (Bisson et al, 2013). Forest residues available in Humboldt County are estimated to provide up to 220 megawatts of energy (Williams et al., 2008). Furthermore, in 2012 biomass energy created by forest residues supplied 60 megawatts of the total energy needs of the county (Marshall and Zoellick, 2012), making energy independence a feasible goal. While biomass resources are plentiful on the Pacific north coast, the conundrum of how to transform forest “waste” into “wisdom” has yet to be solved.

1.2- How Biomass Is Removed

The ideal harvesting method for biomass extraction is integrated harvesting (Jain et al., 2012). Integrated harvesting is whole-tree harvesting that effectively removes limbs and branches as well as boles at the time of treatment and negates the need for returning to the unit to extract forest residues after harvesting is complete, which can often times be very costly, and can even make the operation unfeasible (Jain et al., 2012; Harrill and Han, 2012). In an integrated harvest biomass recovery operation, one of the major cost components is secondary transportation. The hauling cost associated with transporting clean chips and biomass fuels may not be economically feasible, especially with increased hauling distances (Han et al., 2004). Some benefits to integrated harvesting include reduced biomass accumulation within the harvested area, which leads to more fire resistant conditions. Furthermore, integrated harvests facilitate the application of post-harvest treatment by making it easier and safer to navigate within the harvested area. Some draw backs of integrated harvesting is that it requires additional storage space to account for the additional volume of biomass that is being handled within the supply chain, as well as the financial and storage constraints associated with adding

In the absence of integrated harvesting, stands are typically harvested using conventional harvesting systems. In conventional logging systems, trees are felled and processed in the unit leaving tops, limbs, chunks, small diameter and non-merchantable trees which are the result of timber harvest and thinning operations. A typical way that contractors recover biomass in these conditions is known as a CBRO. Local to Humboldt County, biomass contractors use modified high-sided dump trucks that are fitted with skidder tires can be utilized for short distances to extract forest residues to centralized comminution locations where chip trucks have limited access to harvest units due to road conditions, terrain, and slope constraints (Bisson et al., 2015). In these CBRO's, sub-merchantable trees and tree tops are processed into either chips or hog fuel at these locations, and then are either blown directly or belt fed into 92m^3 chip vans and transported with 6WD chip trucks on secondary roads to a staging area accessible by a permanent haul road, where a highway capable chip truck can later come pick up and deliver to the energy facility (Montgomery et al., 2016).

1.3- Limitations And Solutions To Biomass Operations

Delays within the supply chain can have significant negative impacts on the overall efficiency and productivity of CBRO operations, such as causing machines in the supply chain to run idly. Also, delays can necessitate extended residence time of comminution, even at centralized locations. As returning to a harvest site to collect forest residues post-harvest is so costly, special attention should be paid in order to maximize utilization and minimize delays of the equipment involved. Delays can often be avoided by decoupling comminution activities from harvesting activities such that the equipment has a continuous feedstock of biomass and can run at its full utilization rate, thus maximizing its efficiency. Furthermore, comminution operations can be decoupled from secondary transportation to the bio-energy facility by identifying centralized storage locations for biomass within the supply chain. Decoupling the various operations creates a “system balance” which implies that each piece of equipment is realizing its maximum productivity (Bisson et al., 2015).

Previous studies have extensively explored the realm of spatially explicit supply chain design for the whole bioenergy system (Li et al., 2015; Kizha et al., 2015; Tittmann et al., 2010; Parker, 2011; Dunnett et al., 2008). In earlier studies, bioenergy production costs were predicted based on cost estimates for each system component including procurement, site-specific transportation, and conversion costs; sensitivity analysis showed transportation costs have significant impact on the optimal system configuration and normalized biofuel production costs, which indicates potential advantages of increasing the efficiency of biomass feedstock transport (Li et al., 2015; Harrill and Han, 2012; Han et al., 2004). In a recent study, conventionally harvested stands can be uneconomical to return to solely on the basis of harvesting biomass unless there is enough to supply at least one 9 hour work day and could supply 21 (92 m^3) chip trailer loads with 15BDmT per day (Montgomery et al., 2016); which can yield a product that is currently worth \$30-\$50/Bone Dry Ton (BDT) depending on the distance of secondary transportation (Bisson et al., 2015). In the case of Bisson et al., 2015, total hauling costs at low to moderate hauling distances (13 miles – 57 miles one-way) were reported to be \$30.39/BDT, which accounted for 31% of the total system cost of \$44.30/BDT. This is further corroborated in other studies that found distances greater than 61 miles increases total system costs above \$30/BDT (Kizha. et al., 2015). This indicates that at moderate to extended hauling distances (greater than 57 miles), CBRO operations can be limited by transportation, thus highlighting the necessity for minimizing transportation costs within a CBRO supply chain.

1.4- Value-Added Products Through Thermal Conversion

Torrefaction is a thermal-chemical treatment method that is carried out at temperatures between 200C and 300C in the absence of oxygen (Bergman and Kiel, 2005). Torrefaction not only destructs the fibrous structure and tenacity of biomass, but it is also known to increase the calorific value (Van der Stelt et al., 2011). Torrefaction is a very promising technology due to its high process efficiency compared to pelletization; and combined with pelletization, it can have an energy content as high as 20.4-22.7GJ/ton

(Uslu et al., 2008). It also has potential to increase efficiency of biomass feedstock handling and logistics by increasing feedstock energy density and flowability. Furthermore, it reduces energy use in grinding and refining, cost for feedstock storage and transportation, and greenhouse gas and pollutant emissions associated with the feedstock supply chain (Bergman, 2005; Uslu et al., 2008; Deutmeyer et al., 2012).

Some storage problems associated with un-converted biomass is the rotting behavior exhibited by material with high moisture content. Once torrefied, however, converted biomass has a low moisture content and more hydrophobic characteristics that together reduce the rotting behavior associated with un-converted biomass and can make storage easier (Van der Stelt et al., 2011). Processing harvest residues with these techniques can increase the value of the feedstock (Uslu et al., 2008). However, hauling chips to the trailer yard has been reported as the least productive stage of the residue recovery process (Harrill and Han, 2012), highlighting the importance of optimizing the logistics of CBRO’s. Harvest residues generally have low bulk densities and irregular configurations, making it difficult to reach a truck’s payload, which causes the transportation of biomass within recovery operations to be costly (Wolfsmays and Rauch, 2014; Rentizales et al., 2009). This can drastically reduce the feasibility of operations such as trucks not operating at their maximum potential utilization.

With value-added products such as biochar, torrefied pellets, or briquettes, managers may be able to reduce average costs of transportation by 16.7% and average total delivered costs by 7.7% compared to systems that do not include pretreatment (Li et al., 2015). Through the use of conversion technologies, forest residues can even better offset the high operational costs of integrated harvesting while supplying a renewable energy source. Emerging international bio-energy markets have the capacity to consume up to US $1.6 trillion per year (Faaij and Domac, 2006).

Commonly, BCT's are stationary, located generally close to the energy facility, and can create a product which is worth ~$200/BDT (SERC, personal communication). Two primary benefits from the use of BCT's are 1) an increase in energy density which makes it more efficient in satisfying the demand for feedstocks at the bio-refineries on a mass basis and 2) the increased mass density increases the transportation efficiency by reducing the transportation cost ($/(ton.mile)), especially for rail transportation (Li et al., 2015). Some possibilities in the future would incorporate pre-treatment technologies and/or BCT's for in-woods treatment prior to extended secondary transportation.

1.5- Waste To Wisdom Project

The *Waste to Wisdom* project is a federally funded look into the problem of how to manage commercially un-valuable leftover forest residues. The project incorporates 15 teams nationwide from several task areas to find a solution that can turn wasted biomass into valuable energy and/or bio-based products. Teams look at feedstock and BCT development, as well as logistics and sustainability analysis, in effort to improve economic efficiency of transporting a traditionally low value product.

More specifically, the project individually studies the many aspects of integrating a BCT into the feedstock supply chain in order to determine optimal system configurations. This begins in the harvest unit with sorting and arranging of biomass with emphasis on minimizing contamination, facilitating comminution, improving moisture content control, and improving handling efficiency. Next, through productivity studies, comminution equipment used to produce high quality feedstocks that are suitable for treatment with a BCT are identified. Similarly, new screening technologies that can improve handling in the BCT will also be identified.

Once identified, this equipment can be incorporated into landscape level planning and logistics models in order to maximize net revenues and reduce adverse environmental impacts. Some potential benefits of this project include offsetting the costs of forest restoration and fire hazard treatments while simultaneously facilitating follow-up management operations. Other benefits to the project are that the use of bio-based products is assumed to improve air quality and reduce greenhouse gas emissions, sequesters carbon, can be used as a restoration tool to amend soil, and stimulate economic growth of rural communities, all while reducing reliance on unsustainable fossil fuels.

1.6- Objectives

The first objective of this study is to develop two potential models integrating a BCT into a CBRO supply chain. The Logistics Model 1 will consider that comminution and BCT operations will occur at the same site. The Logistics Model 2 will consider that comminution operations will occur at separate sites from BCT operations. Each model will have three scenarios that represent various availabilities of biomass on a Bone Dry Ton/Acre (BDT/AC) basis. For both models, a spatial analysis will be performed to identify candidate sites that meet the various footprint and slope requirements for either model/scenario.

The second objective is to minimize transportation time associated with the models. A network analysis of the candidate sites will determine which are optimally placed to give the shortest travel time from a chosen number of facilities to a determined number of demand points, calculating both average and total one-way travel time. A sensitivity analysis will be performed in order to determine the logistic effect of increasing the number of BCT sites within any given model and give conclusive results of which model exhibits shorter travel times.

The third objective is to determine the impact of the number of BCT locations on transportation time. This will be accomplished using a sensitivity analysis. Results can then be applied to system balance equations in order to make equipment recommendations. These recommendations can be used to better understand the financial needs of setting up a BCT integrated CBRO, as well as to make informed decisions regarding the optimal number of BCT sites within a CBRO.

PROPERTY DESCRIPTION

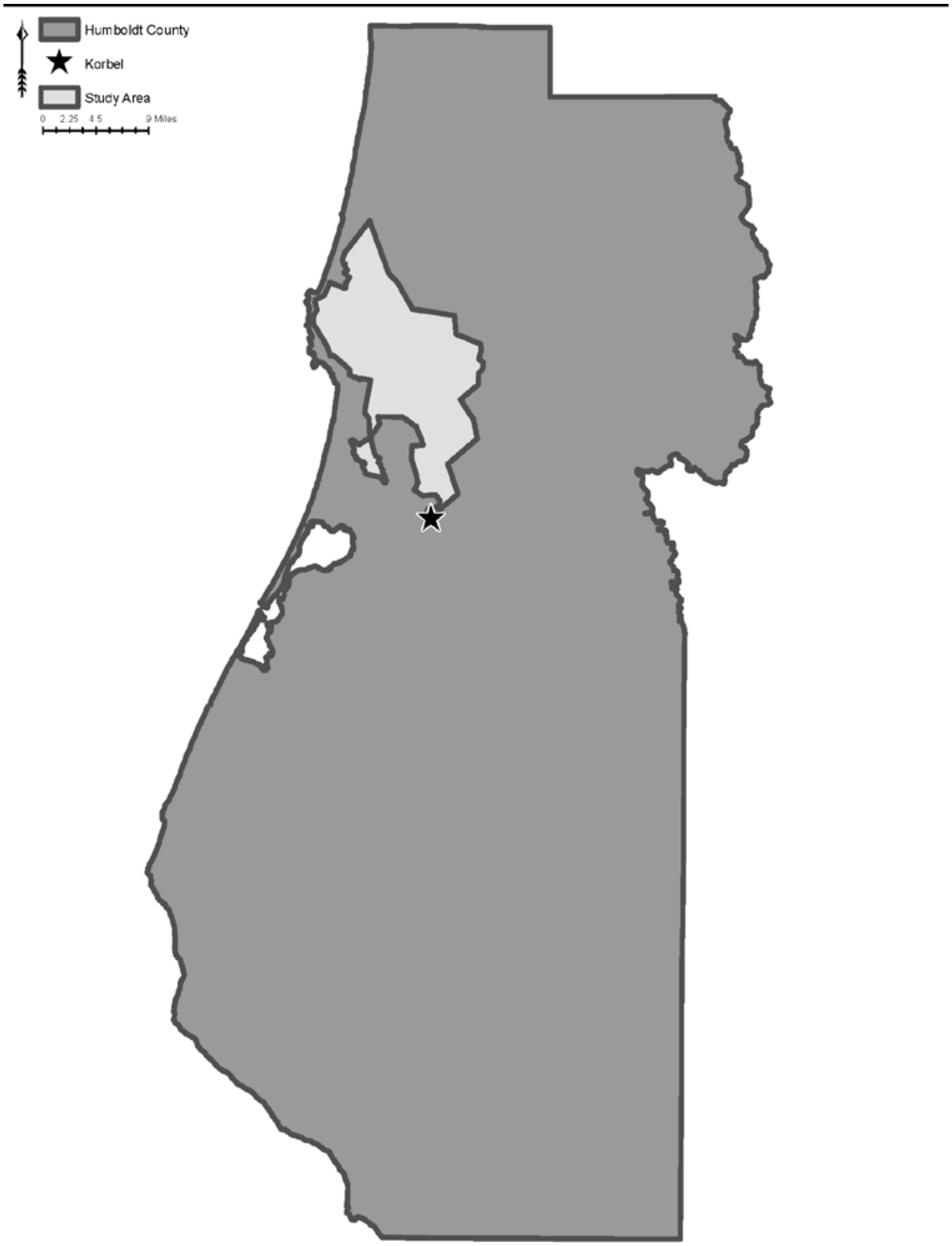


Figure 2- Study site location within Humboldt County, Ca., shown in relation to Korbel, Ca.

The study area encompassed 101,661 acres of industrial timberland extending approximately 24 miles north of Korbel, Ca (40°52′13″N, 123°57′30″W) (Figure 2). The property is owned and managed by Green Diamond Resource Company (GDRC), which is a certified Forest Stewardship Council (FSC) company. The FSC mission is to promote environmentally sound, socially beneficial and economically prosperous management of the world's forests. Typical silvicultural practices of a large portion of the property are described as even-age management. Units are typically harvested using either single pass shovel logging or cable logging depending on slope and environmental limitations. After harvesting is completed, biomass is traditionally piled into “teepee” shape piles with a shovel and left in the unit, which are later burned during permissive time frames. The primary tree species on the property are *Sequoia sempervirens* (Coast Redwood), *Pseudotsuga menziesii* (Douglas-fir), *Tsuga heterophylla* (Western Hemlock), and *Notholithocarpus densiflorus* (Tanoak). However, composition can vary greatly depending on proximity to coast. Near pure stands of coast redwood distribute in area where coastal fog commonly reaches, whereas more mixed conifer stands with Douglas-fir, Western Hemlock, and Tanoak exist toward the eastern interior.

MATERIALS AND METHODS

Integrating BCT equipment into the supply chain of a CBRO operation typically comes with many stringent requirements set by the equipment itself and are related to area, topography, Watercourse and Lake Protection Zone (WLPZ)/ Equipment Exclusion Zone (EEZ) buffers and road access. Geographic Information System (GIS) based environmental decision support systems (EDSS) have been developed for a variety of environmental planning and management, ranging from prioritizing prescribed burning activities (Hiers et al., 2003) to more specifically in the context of optimal planning of forest biomass use for energy production (Frombo et al., 2009; Noon and Daly, 1996; Nagel, 2000). Operationally, Alfonso et al., (2009) developed a methodology that can analyze wide geographic areas by making subdivisions and considering a potential biomass plant in each subdivision. More locally, Montgomery et al., (2016) created a work plan logistic model for a centralized biomass recovery operation in Humboldt County has been created using the Network Analyst toolbox in ArcGIS. This model was developed with the delivered product being comminuted material for use at a local bioenergy facility. Using a similar model, managers can identify sites for placing BCTs in the forest which minimizes transportation times, minimize the move in and move out costs in time and real dollars, and increase transportation efficiency because converted wood chips are more economical to haul than green wood chips.

For this study, road, watercourse, and harvest/silvicultural information has been provided by Green Diamond Resource Company (GDRC). DEM has been provided by

United States Geological Survey (USGS). Machine rate and footprint information for the BCTs has been provided by Schatz Energy Research Center (SERC).

3.2- Spatial Analysis And Suitability Analysis

The necessary GIS data layers used for spatial analysis are a Digital Elevation Model (DEM), hydrology shapefile including all class 1, 2, and 3 streams, roads shapefile including road surface type (paved, rocked, dirt), harvest-unit shapefile including all silvicultural management plans and boundaries of harvest units for 2014-15. Before models could be created, I first had to identify how many candidate sites existed and where they were within the project area; furthermore, each candidate location had a number of attributes involved with its selections. First, buffers were created to eliminate any potential Watercourse and Lake Protection Zone (WLPZ). Part of the requirements of a BCT is that it be on relatively flat ground. To incorporate this, a Digital Elevation Model (DEM) was used to classify and select areas that were less than or equal to 3% slope. Then, the geometric areas for each site were calculated and allocated to the logistics models which required said areas. It was important that the proposed models must provide permanent road access as well. To account for this, flat sites that met the spatial requirements of a given scenario, and not within a WLPZ were intersected with permanent road segments in the project area to give the final candidate locations that will be used in the network analysis models.

Based on the volume of biomass that needs to be processed as well as if the operations within the supply chain are coupled or de-coupled, any given scenario can have spatial requirements that vary quite significantly. Logistics Model 1 assumes biomass recovery for 200 days per year, BCT operations for 250 days per year, and between 0.73 acres and 5.23acres of space for equipment and storage. Logistics Model 2 assumes biomass recovery for 100 days per year, BCT operations for 250 days per year, and between 1.1 acres and 12.61 acres of space for equipment and storage. Because the number of biomass collection days compared to the number of BCT operation days is not 1:1, each model needed to account for different storage volumes of biomass at BCT sites. To spatially represent this conundrum, the models have incorporated footprint calculations provided by SERC regarding the needs of a BCT site. First, I calculated areas required by the different scenarios based on scope and scale of the Waste to Wisdom project guidelines (Figure 4). Next, I selected candidate sites that met the spatial criteria of a given scenario and created a new shape file with the selection. Lastly, I calculated the amount of assumed recoverable biomass per harvest unit by multiplying the total harvest unit acres by the assumed BDT/ac of recoverable biomass for any scenario.

For centralized conversion sites within the Logistics Model 1, there were three potential scenarios considered in terms of recoverable biomass per acre, all of which have been generalized in order to easily represent them in respective attributes of the harvest unit shapefile, as well as to easily represent a low (15 BDT), moderate (30 BDT), and high (50 BDT) volume of recoverable biomass that could potentially occur across a wide range of landscapes. Scenario 1 accounted for 50 BDT per acre, Scenario 2 accounted for 30 BDT per acre, and Scenario 3 accounted for 15 BDT per acre. Within Logistics Model

2, Scenario 4 considered 50 BDT per acre, Scenario 5 considered 30 BDT per acre, and Scenario 6 considered 15 BDT per acre.

Once I began analysis of spatial data, it was determined that assuming a coupled operation was not feasible for many situations due to the large storage space required for biomass in the supply chain. It was determined that if biomass was to be stored at the BCT site, then Logistics Model 1- Scenario 3 was the only one that was *less* than 3 acres; however, if biomass can be delivered to BCT sites as needed, then Logistics Model 2- Scenario 4 is the only one that is *greater* than 3 acres (Table 1). The result of this is that both models will assume that biomass can be forwarded to BCT sites as needed, which de-couples (w/o storage) the supply chain at the BCT site. Spatially, for centralized processing sites within the Logistics Model 1, Scenario 1 will account for 2.34 acres, Scenario 2 for 1.45 acres, and Scenario 3 for 0.73 acres (Table 1). Centralized comminution locations within Logistics Model 2 will account for 0.22 acres. For centralized conversion locations within Logistics Model 2, Scenario 4 will account for 3.57 acres, Scenario 5 will account for 2.17 acres, and Scenario 6 will account for 1.1 acres (Table 1).

Table 1 - Spatial requirements associated with each Logistics model and associated scenarios.

	Required Acres (w/o storage)		**Required Acres (w/storage)**	
	Comminution	BCT	Comminution	BCT
Model 1, Scenario 1	N/A	2.34	N/A	5.23
Model 1, Scenario 2	N/A	1.45	N/A	3.27
Model 1, Scenario 3	N/A	0.73	N/A	1.64
Model 2, Scenario 4	0.22	3.57	0.22	12.61
Model 2, Scenario 5	0.22	2.17	0.22	7.65
Model 2, Scenario 6	0.22	1.1	0.22	3.83

In order to use the network analyst toolbox, I will first need to amend the road network data. To do this, I applied an average travel speed of 14.6 MPH (Han et al., 2012) to gravel forest roads which were within the study area (Table 2). Next I merged forest road data with public road data that assumes legal speed limits for all paved roads that ranged between 15 MPH to 65 MPH (Table 2). A quick analysis of summary statistics in the road network attribute table indicated that the majority of roads encountered assumed 25 MPH transportation speed (Figure 3).

Table 2 - Road speeds (MPH) associated with different road types

MPH	Road Type
14.6	Forest Roads (Rocked)
14	Public Roads (Paved)
25	Public Roads (Paved)
30	Public Roads (Paved)
35	Public Roads (Paved)
45	Public Roads (Paved)
50	Public Roads (Paved)
55	Public Roads (Paved)
65	Public Roads (Paved)

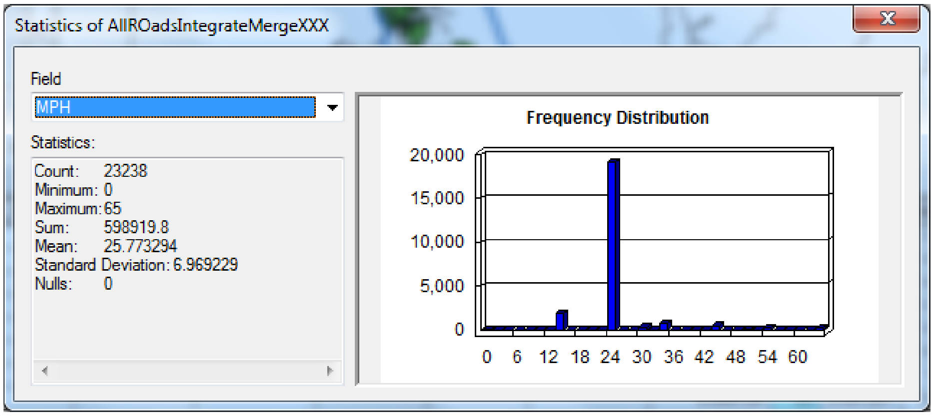


Figure 3- Road network statistics summary generated by ArcMap

					Central landing				BCT Site								
Scenario	Scale	volumes/acre	Field Ops Season	Landing Use	Baler	Chipper	Grinder	BCT Ops Season	Chipper	Grinder	Star Screener	Deck Screener	BCT Power Source (grid, diesel, gasifier)	Dryer?	Biochar ?	Torrefier?	Briquetter?
1	30-50,000 tpy	30-50 BDT	200 days	Processed tops trucked out, limbs baled	X			250 days	X	X	X		Diesel/grid/gasifier	X	X	X	X
2	15-30,000	15-30	200 days	Processed tops trucked out, limbs baled	X			250 days	X	X	X		Diesel/grid/gasifier	X	X	X	X
3	6?-15,000	6-15	200 days	Processed tops trucked out, limbs baled	X			250 days	X	X		X	Diesel/grid/gasifier	X	X	X	X
4	30-50,000 tpy	30-50 BDT	100 days	Processed tops chipped, limbs burned		X		250 days			X		Diesel/grid/gasifier	X	X	X	X
5	15-30,000	15-30	100 days	Processed tops chipped, limbs burned		X		250 days			X		Diesel/grid/gasifier	X	X	X	X
6	6?-15,000	6-15	100 days	Processed tops chipped, limbs burned		X		250 days				X	Diesel/grid/gasifier	X	X	X	X

Figure 4- Waste to Wisdom project guidelines.

3.3- Network Analysis Logistics Modeling

After the spatial analysis has been completed, the models can be built using the Network Analyst tool set. The ArcGIS Network Analyst tool set provides network-based spatial analysis tools for solving complex routing problems. The tools utilize a configurable transportation network data model, which makes it possible for organizations to accurately represent their individual network requirements, such as travel speed and distances between facilities and demand points. Users can plan routes for an entire fleet, calculate drive-times, locate facilities and solve other network related problems (www.esri.com, accessed 10/2015).

This study used the Location-Allocation tool within the Network Analyst extension to generate total and average one-way travel times for analysis of each model. Total one way travel time can be thought of as the sum of network costs (time) that occur as a result of traveling between demand point and facility. Whereas this is not a true total that accounts for multiple round trips, it can then be thought of as a metric to compare the effectiveness of Logistics models and their associated scenarios. The models used the Maximize Market Share problem type, which selects facilities to maximize the market share of a given set of demand points (in this case BDT of biomass/acre among candidate biomass recovery units) in the presence of competitive facilities. This means that with each BCT site change, there was the most amount of biomass allocated to it possible. Accordingly, Logistics Model 1 was the first network model developed in this study. This model describes a CBRO in which both comminution and conversion activities occur at the same centralized site and calculates total and average one-way travel times. The Logistics Model 1 will begin the supply chain at the harvest units, where processed tops are picked up from permanent roadside decks and delivered to centralized conversion sites located within the project area. From centralized conversion sites, the next section of the supply chain models converted biomass that is hauled to the market, which in this study is assumed to be the DG Fairhaven Power Company in Humboldt County, Ca.

Logistics Model 2 is the second model that was developed. This model again described a CBRO and calculated total and average travel times; however, comminution and conversion activities occurred at separate locations. The Logistics Model 2 will begin the supply chain at the harvest units, where processed tops are picked up from permanent roadside decks and delivered to one of 20 centralized chipping-only sites. The second section models the movement of chipped material from centralized chipping-only sites to centralized conversion sites. From centralized conversion sites, the next section of the supply chain models converted biomass that is hauled to the market, which again is assumed to be the DG Fairhaven Power Company in Humboldt County, Ca.

Impedance cutoff in these models refers to the maximum transportation time that the model will consider while determining travel times from a chosen number of facilities to the determined set of demand points. Impedance cutoff values for all sections of the models were adjusted to access all demand points from the chosen facilities. This was done by setting the impedance cutoff at “1” minute and then running the Location-Allocation tool. It was then determined how many demand points were accessed in that time, which was far less than the total number of demand points. The impedance cutoff was then increased until the model was able to access all of the given demand points.

The number of comminution sites across the project area was selected based on market location as the demand point and comminution sites as the facilities. The model was then run to select the best “1” facility, increasing the number until the model returned “redundant results”, which was 20 in this study. This means that increasing the number of sites past this number will not return a better solutions set. This number was found to be in line with a similar previous study, which cited a biomass contractor who moved the centralized comminution locations 24 times per work year (Montgomery et al., 2016), and was therefore incorporated into my models.

3.4- Modeling Assumptions

Modeling assumptions are as follows:

1. All models and scenarios assume that tops were processed during initial harvest and forwarded to landings that have permanent road access.
2. Self-loading log trucks were used to recover processed tops from landings and deliver to central processing sites.
3. There were at least a one day supply of processed tops available for use at the beginning of each work day, e.g. delivery and comminution/conversion were decoupled by a one day supply.

4. Both self-loading log trucks as well as chip trucks traveled at an average speed of 14.6 MPH on permanent gravel forest roads, and at legal speed limits on public roads.
5. Both the self-loading log truck as well as chip truck can deliver 20 tons of material per load.
6. A typical workday for all equipment in the supply chain was 10 hours long.
7. Loading and unloading time, for both chip trucks and self-loading log trucks, was 30 minutes and 30 minutes, respectively.
8. The chipper can operate at a rate of 35 tons/hour (Bisson et al., unpublished)
9. A Star screener can operate at a rate of 62.5 tons/hour and a Deck screener can operate at a rate of 26.8 tons/hour (Woo et al., unpublished).
10. Chipping/BCT operations will only occur at one site at a time, and that each chosen site within the supply chain will represent one potential move for that season, e.g. 2 BCT sites represents two moves, 5 BCT sites represents 5 moves, etc.

3.5- Sensitivity Analysis

A sensitivity analysis was conducted in order to explore the effect that having multiple BCT sites has on the total and average one-way travel time of either model. Both Logistics Model 1 (Scenarios 1-3) and Logistics Model 2 (Scenarios 4-6) are modeled after 2, 5, 10, 15, 20, 25, 27, and 30 conversion sites across the supply chain. Total, maximum, and average travel time were calculated during network analysis. This can be used as a metric to compare the effect of increasing the number of BCT sites within either CBRO supply chain, to compare the effectiveness of both models at reducing travel time within a supply chain, and to determine how many BCT sites within a supply chain will cause one Logistics model to perform better than the other.

3.6- System Balance

System balance was determined for all iterations of both logistics models which all scenarios within a given Logistics model exhibited shorter travel times than the other. System balance equations used to calculate the number of chippers, self-loading log trucks, chip trucks, and screeners are reported in (Figure 5). System Balance calculations based on BCT equipment (Dryer, Torrefaction, and Briquetter) have been provided by SERC.

$$\text{\# of Chippers} = \frac{\text{Daily Processing Rate of BCT in green tons (SERC)}}{\text{Daily Chipper Production (Bisson et al.)}}$$

$$\text{Self-loading Log Truck loads per day} = \frac{\textit{Daily Extraction Rate in green tons (SERC)}}{\textit{tons per load (DOT)}}$$

$$\text{\# of Self-loading Log Trucks} = \frac{\textit{Self-loading Log Truck loads per day * (((2*Harvest-Com1 Average one-way minutes)+ loading minutes + unloading minutes)/60)}}{\textit{Self-loading Log Truck Hours per day}}$$

$$\text{BCT-Market Chip Truck loads per day} = \frac{\textit{BCT Output (SERC)}}{\textit{Chip Truck tons per load (DOT)}}$$

$$\text{Chipping-BCT Chip Truck loads per day (S4-S6 only)} = \frac{\textit{Chipper Daily Production}}{\textit{Chip Truck tons per load}}$$

$$\text{\# of Chip Trucks} = \frac{\textit{BCT-Market Chip Truck trips per day * (((2* BCT-Market Avg. one-way minutes)+ load minutes + unload minutes)/60)}}{\textit{Chip Truck Hours per day}} + \frac{\textit{Chipper-BCT Chip Truck trips per day * (((2* Chipper-BCT Avg. one-way minutes)+ load minutes + unload minutes)/60)}}{\textit{Chip Truck Hours per day}}$$

$$\text{\# of Screeners} = \frac{\textit{Daily Production Rate of BCT (SERC)}}{\textit{Screener production per day}}$$

Figure 5 - Equations for system balance

RESULTS

Spatial analysis of the data indicated that among 2015 harvest data provided by GDRC, only 187 harvest units intersected a permanent road and were selected as candidate biomass recovery units in this analysis, of which, only 173 were accessible without having to traverse a seasonal road (Table 3). The result of this is that the greatest number of harvest units considered in the network analysis is 173 demand points that were accessed in the location-allocation analysis. For Logistics Model 2 exclusively, there were 236 comminution sites located (Table 3). Logistics Model 1 located between 83- 59 BCT sites where Logistics Model 2 located 64-136 BCT sites (Table 3).

Table 3 - Spatial Analysis results for a de-coupled system

Suitability Analysis/ Candidate sites (w/o storage)			
	Harvest Units	Comminution Sites	BCT Sites
Model 1, Scenario 1	187	N/A	83
Model 1, Scenario 2	187	N/A	114
Model 1, Scenario 3	187	N/A	159
Model 2, Scenario 4	187	236	64
Model 2, Scenario 5	187	236	86
Model 2, Scenario 6	187	236	136

The results of the location-allocation analysis indicated that fewer processing sites within the supply chain will reduce total travel time. This can be attributed to the additional transportation time required to forward comminuted biomass to centralized conversion sites. The network analysis results for Logistics Model 1 were calculated for each scenario in terms of total and average one-way travel time. Furthermore, total and average travel times were calculated and recorded for each section of the supply chain, e.g. harvest unit to conversion site, conversion site to market. Appendix A reports the results of network analysis for each iteration of the sensitivity analysis. The network analysis results for Logistics Model 2 were calculated for each scenario in terms of total and average one-way travel time. Furthermore, total and average travel times were calculated and recorded for each section of the supply chain, e.g. harvest unit to conversion site, conversion site to market. Again, Appendix A reports the results of network analysis for each iteration of the sensitivity analysis.

When total travel times for the three scenarios within each Logistics model are averaged together, the results of the sensitivity analysis indicated that Logistics Model 1 returned shorter travel times than Logistics Model 2 model in most applications (Figure 6- Figure 7). This is attributed to the fact that Logistics Model 1 avoided excess in-woods transportation by combining comminution and BCT operations.

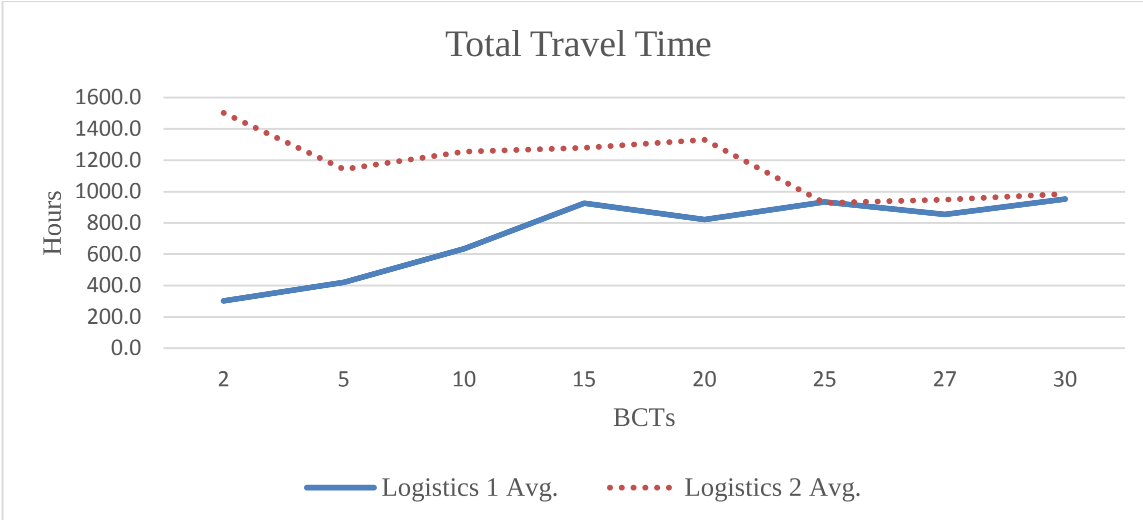


Figure 6- Total one-way travel time averaged together for Logistics Model 1-Scenarios 1-3 and Logistics Model 2- Scenarios 4-6.

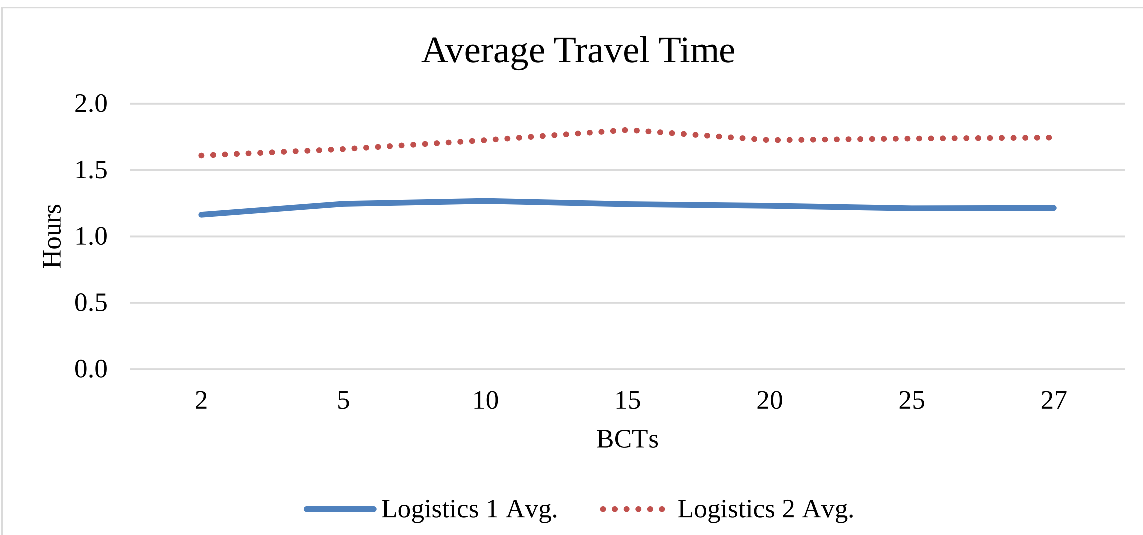


Figure 7- Average travel times for Logistics Model 1-Scenarios 1-3 and Logistics Model 2-Scenarios 4-6.

Figure 8, Figure 9, and Appendix B graphically illustrate the results of each logistics model scenario. Logistics Model 1 returned shorter travel times across the board when the number of BCT sites was 10 or less. Unclear results occurred when the number of BCT sites was increased past 10. In the interval between 15 and 20 BCT sites, the Logistics Model 1 exhibited shorter travel times, except for the 50BDT/ac scenarios, 1 and 4. When the number of BCT sites reached 25, the Logistics Model 1 also returned shorter travel times, but scenario 6 (Logistics Model 2, 15BDT/ac) yielded shorter travel times than scenario 3. At 27 BTC sites, the Logistics Model 1 performed best across the board; however, all results were very close to each other compared to many of the other iterations. When the number of BCT sites was increased to 30, Logistics Model 1 returned shorter travel times, except for the 15BDT/ac scenarios, 4 and 6; likewise in the case of 27 BTC sites, the differences among results seemed minor. When average travel times for individual scenarios of both Logistics models are averaged together, Logistics Model 1 returned shorter travel times than Logistics Model 2 across the board.

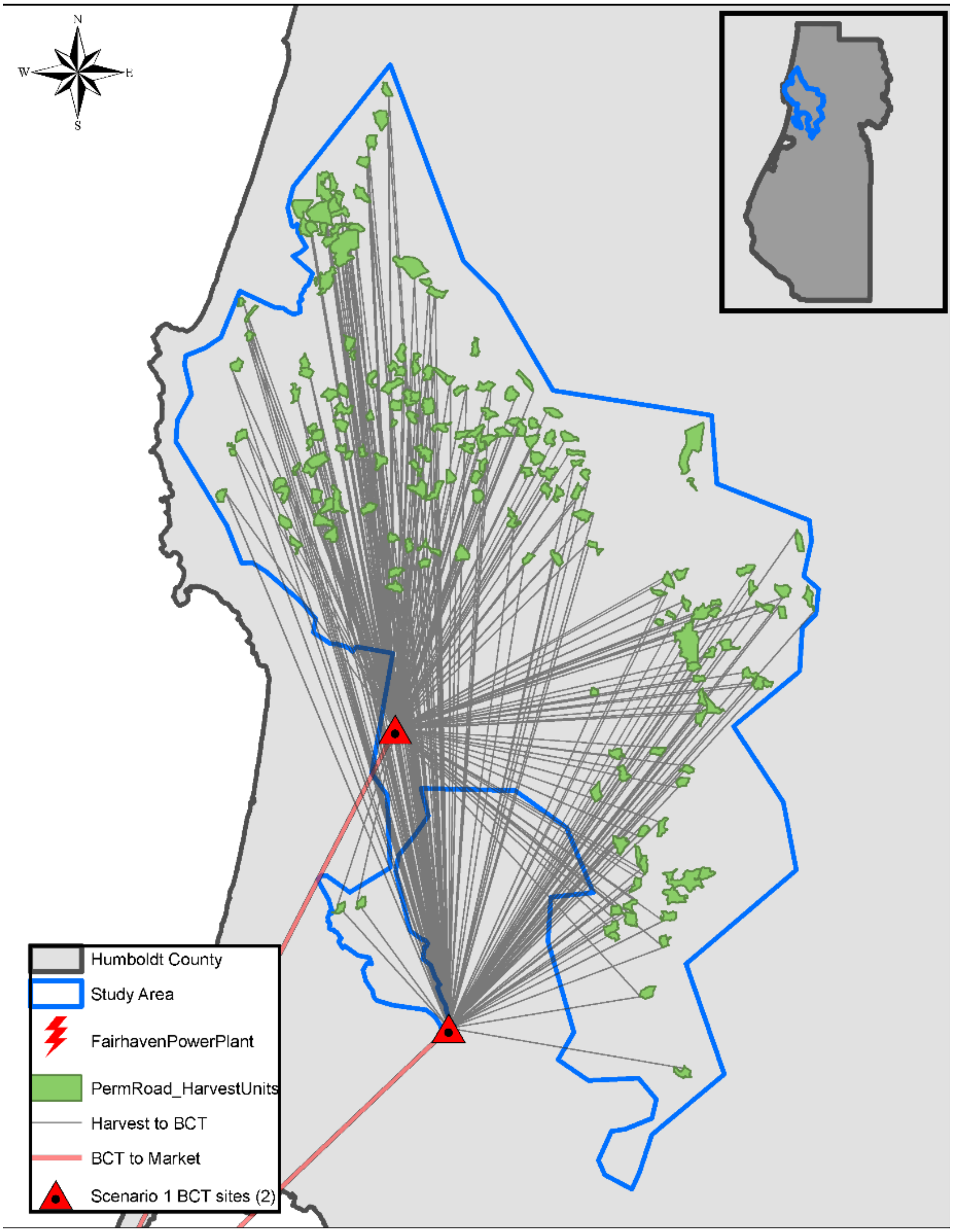


Figure 8- Logistics Model 1”- (2 comminution + BCT sites)

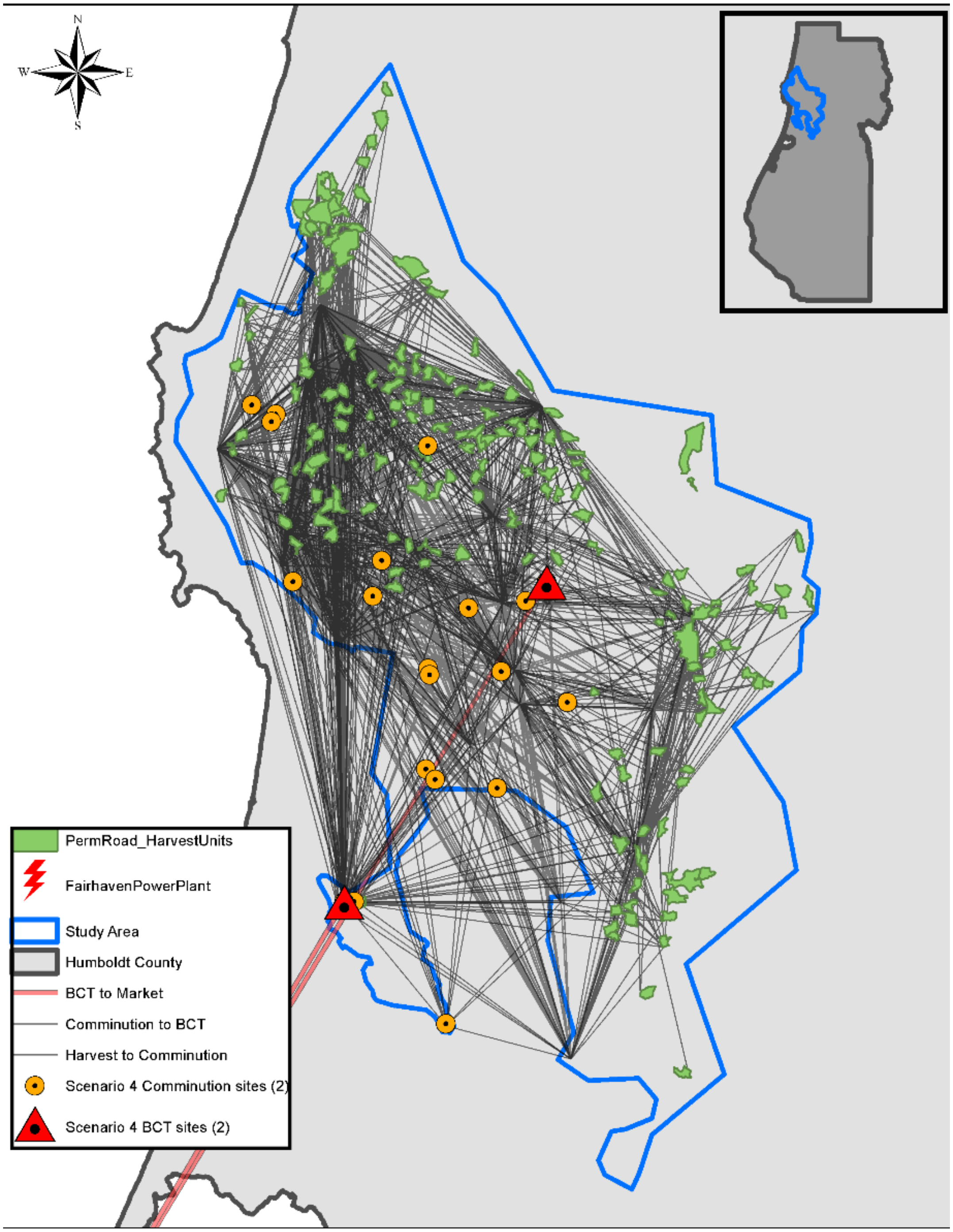


Figure 9- “Logistics Model 2” - (20 comminution sites, 2 BCT sites)

System balance was only determined for 2, 5, and 10 BCT site models because they exhibited conclusive results. Conclusive results means that all scenarios within a Logistics model exhibit either more or less travel time than the other. Inconclusive results past the 10 BCT sites of both Logistics models returns variances between shortest travel times in terms of given scenarios. In terms of system balance based on the assumptions, 2, 5, and 10 BCT iterations of the Logistics Model 1 will require one chipper, 1-3 self-loading log trucks, 1-2 chip trucks, and one screener (Table 4). The same iterations of the Logistics Model 2 will require one chipper, 2-6 self-loading log trucks, 4-5 chip trucks, and one screener (Table 4). Assumptions used while calculating system balance are displayed on (Table 5).

Table 4- System balance of Logistics Model 1 (Scenarios 1-3) and Logistics Model 2 (Scenarios 4-6)

					Reported by SERC		
	Chippers	**Self-loading Log Trucks**	**Chip Trucks**	**Screeners**	**Dryers**	**BCTs**	**Briquetters**
System Balance 2 BCT sites							
Model 1, Scenario 1	1	3	2	1	3	27	12
Model 1, Scenario 2	1	2	1	1	2	16	7
Model 1, Scenario 3	1	1	1	1	1	8	4
Model 2, Scenario 4	1	6	5	1	3	27	12
Model 2, Scenario 5	1	4	5	1	2	16	7
Model 2, Scenario 6	1	2	5	1	1	8	4
System Balance 5 BCT sites							
Model 1, Scenario 1	1	3	2	1	3	27	12
Model 1, Scenario 2	1	2	1	1	2	16	7
Model 1, Scenario 3	1	1	1	1	1	8	4
Model 2, Scenario 4	1	6	5	1	3	27	12
Model 2, Scenario 5	1	3	5	1	2	16	7
Model 2, Scenario 6	1	2	5	1	1	8	4
System Balance 10 BCT sites							
Model 1, Scenario 1	1	3	2	1	3	27	12
Model 1, Scenario 2	1	2	1	1	2	16	7
Model 1, Scenario 3	1	1	1	1	1	8	4
Model 2, Scenario 4	1	6	5	1	3	27	12
Model 2, Scenario 5	1	3	5	1	2	16	7
Model 2, Scenario 6	1	2	4	1	1	8	4

Table 5- Assumptions used while calculating system balance

Assumptions		
Self Loading Log truck	20	Tons/load
Chip Truck	20	Tons/load
Work day (Self-loading Log Truck)	10	hours/day
Work day (BCT-Market Truck)	10	hours/day
Work day (Screener)	10	hours/day
Work day (Chiper-BCT Truck)	10	hours/day
Work day (Chipper)	10	hours/day
Load time Chip Truck	30	Min
Unload time Chip Truck	30	Min
Load Time Log Truck	30	Min
Unload Time Log Truck	30	Min
Chipper	35	BDT/hr
Star screener	62.6	BDT/hr
Deck screener	26.8	BDT/hr
Self-Loading Log truck L1S1	12.5	trips/day
Self-Loading Log truck L1S2	7.5	trips/day
Self-Loading Log truck L1S3	3.8	trips/day
Self-Loading Log truck L2S4	25.0	trips/day
Self-Loading Log truck L2S5	15.0	trips/day
Self-Loading Log truck L2S6	7.5	trips/day
BCT-Market Chip Truck L1S1	6.8	trips/day
BCT-Market Chip Truck L1S2	4.0	trips/day
BCT-Market Chip Truck L1S3	2.0	trips/day
BCT-Market Chip Truck L2S4	6.8	trips/day
BCT-Market Chip Truck L2S5	4.0	trips/day
BCT-Market Chip Truck L2S6	2.0	trips/day
Chipping-BCT Chip Truck L2S4	17.5	trips/day
Chipping-BCT Chip Truck L2S5	17.5	trips/day
Chipping-BCT Chip Truck L2S6	17.5	trips/day

DISCUSSION

This study set out to model two potential BCT integrated CBRO supply chains. Also, I looked to minimize the transportation time associated with either model. Lastly, I wanted to identify the impact of increasing the number of BCT sites within the supply chain, and determine equipment recommendations for a BCT integrated CBRO supply chain based on those results. I found that the feasibility of biomass as a feedstock for bioenergy production depends on the availability of a market value of materials to support the operational cost incurred in the supply chain, namely in transportation costs (Harrill and Han, 2012; Han et al., 2004). Additionally, in determining the feasibility of bioenergy operations, it is necessary to know how much it would cost to supply a given energy production plant with a given amount of wood fuel (Noon and Daly, 1996). I found one of the largest limiting components is secondary transportation costs, which are shown to account for nearly 50% of total operational costs (Pan et al., 2008), and as such should be a priority when organizing any operation. Reducing secondary transportation costs can potentially be accomplished by removing the harvest residues as value added bioenergy feedstock products, which is increasingly becoming an achievable approach (Han et al., 2010). Biomass Conversion Technologies (BCT) such as torrefaction, gasification, pyrolysis, and densification (palletizing and briquetting) technologies can convert biomass, into dense energy carriers that are easily handled and transported (Uslu et al., 2008).

In this study, the models considered in-woods biomass collection for either 200 days per year (Logistics Model 1) or 100 days per year (Logistics Model 2). Within these models, saw log tops were processed down to 2 inches in the unit and sorted at the landing, which effectively minimized organic contamination and ash content of feedstock, ultimately improving the final quality of product. In these models, the number of biomass collection days was less than the number of operable BCT days/year. As a result, a large area was needed to store the additional volume of feedstock the BCT required to operate for the additional days when biomass collection was not possible due to accessibility issues. This storage constraint can pose a significant setback in projects that exhibit steep topography such as the Pacific Northwest United States, and in some cases can make a project spatially unfeasible.

To solve this problem, processed tops can be decked on the side of permanent roads near or within harvest units. Within the scope of this study, 66% of the harvest units in this analysis have permanent road access, which is defined as either paved or rocked roads providing year-round accessibility. Assuming biomass recovery units have permanent road access or that processed tops can be forwarded to temporary log decks, the storage constraint no longer exists because collection and transportation with a self-loading log truck is possible year round. With this, managers only need to store one to two work days of material at the BCT site, which would significantly reduce the overall footprint of the operation. By arranging your supply chain in such a way, the utilization rates of all equipment within the supply chain can be maximized, while minimizing the problems associated with access, seasonality, and storage of recoverable biomass.

An operational workflow for projects that exhibit this type of problem would be to prioritize biomass recovery in harvest units that have seasonal access during the appropriate season. After seasonal units have either been recovered or restricted in access, trucks can gather processed tops from biomass recovery units with permanent road access to supply comminution/BCT locations with the necessary volume to continue operations. By only storing enough processed tops at any given comminution location to operate for the next work day, problems associated with storage of large volumes of feedstock are significantly reduced and the productivity and utilization of equipment is improved.

Another problem that was identified in this study is related to system balance. It was determined that the chipper is the major bottleneck. System balance considered a large chipper because that is the one that is used/available locally. As a result of its high productivity, the chipper was able to produce ~150 tons per day more than was required by the BCT to meet project production goals. This means that unless there is adequate storage or a market that is capable of accepting excess unconverted chips, then the chipper is likely going to need to be downsized to more appropriately match the production of the BCT, which would alleviate the bottleneck in the supply chain.

Another point that should be highlighted is the importance of planning in biomass recovery operations. If appropriate planning is applied during the harvest planning process, an integrated harvest can be utilized, which is the preferred method of biomass recovery. This method is preferred because processed tops can be handled and removed in the initial harvest and avoids the re-entry costs. Although this study considered exclusively in-woods operations, it should be highlighted that if appropriate planning and integrated harvesting techniques are utilized, tops can preferably be forwarded to existing mill sites or industrial log yards for treatment with a BCT as opposed to in-woods treatments.

While running the many iterations of these models, one thing that I noticed was that the analysis tended to select sites that were closer to the edge of the study area. This indicates that the models are selecting locations that are closer to paved roads because the study area boundary is generally near to a paved public road. Following the theory that sites are chosen based on proximity to paved public roads, mill sites would be preferred for placing BCT equipment. The reason that the models prefer sites that are near paved public roads is because transportation time is minimized when traveling on a paved vs. rocked road. There are also a variety of other reason for placing BCTs at existing mill sites. First, mill sites are already centrally located in the context of converting raw material into value added products, e.g. saw logs being milled into lumber or processed tree tops converted into biochar. Another benefit of placing BCT equipment at existing mill sites is the availability of a power grid. Being able to connect equipment to a reliable and continuous power supply avoids the financial and environmental costs associated with auxiliary diesel power generation. Similarly, positioning BCT equipment in such a way avoids many environmental constraints such as WLPZ/EEZ and fire restrictions, while simultaneously avoiding repetitive and expensive moves of BCT equipment from in-woods site to in-woods site.

CONCLUSION

Treatment with a BCT at centralized locations can effectively increase the secondary transportation efficiency of a CBRO for several reasons. First, by utilizing models similar to the ones developed in this study, managers can effectively minimize transportation time and its associated costs within a BCT integrated CBRO supply chain across a variety of applications. There are other fringe benefits that occur as a result of treatment with a BCT as well. For example, the moisture is removed from the comminuted material prior to extended hauling, which decreases the fuel consumption and increases efficiency of chip trucks. Also, the product being hauled would be worth exponentially more than raw forest residues, easing transportation constraints and increasing the feasibility. Furthermore, CBRO/BCT operations can be incorporated into other operations such as salvage, fuel reduction thinning, and stand conversion which treat commercial conifers as well as non-commercial species of hardwoods and shrubs. Logistically, arranging comminution and BCT operations to occur at the same in-woods site (eg. Logistics Model 1) returned shorter total and average travel times than arranging the two activities to occur at separate in-woods sites, e.g. Logistics Model 2. This was attributed to the additional in-woods hauling time incurred between comminution and BCT sites. The reason that this time was not more productive is because comminution and BCT sites were spatially too close to each other. This logistically created a “ping-pong” effect in-woods between comminution and BCT sites, which is the reason Logistics Model 1 had shorter hauling times (Figure 8 and Figure 9). Ideally, processed tops should be handled as logs and forwarded to a more permanent central location in order to utilize the economy of scale for processing into value-added products. If the comminution must occur in-woods, BCT sites should either be located at the same site as comminution, or should be placed further down the supply chain, e.g. closer to the market/on-grid, in order to avoid the two activities compounding the transportation time and logistics as well as to facilitate extended hours of operations.

This study was done in conjunction with the Waste to Wisdom project, which seeks to identify how to best utilize forest residues. This study has evaluated the project guidelines as developed by the Waste to Wisdom Principal Investigators and the United States Department of Energy. Some possibilities for future studies that may improve this research would be to investigate the same theoretical models and scenarios of this study while incorporating more than one privately owned timberland into the study area. Another potential study is to investigate the effect of an on-grid BCT site in conjunction with in-woods comminution, and if there is an optimal ratio of where to place equipment in the supply chain. A third possibility for future research would include developing a volume equation related to recoverable biomass in the region and apply it to this studies Logistics models while incorporating a study area with greater extent, such as at the county or regional level.

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APPENDIX A

	Model Results: 2BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L1, Scenario 1	11972.6	0.0	49.4	12022.0	200.4
L1, Scenario 2	11816.3	0.0	55.4	11871.7	197.9
L1, Scenario 3	30596.5	0.0	71.6	30668.1	511.1
L2, Scenario 4	111023.4	1027.7	70.8	112121.8	1868.7
L2, Scenario 5	67419.9	1223.9	60.5	68704.2	1145.1
L2, Scenario 6	88098.2	1292.2	69.0	89459.5	1491.0
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	38.3	0.0	24.7	62.9	1.0
L1, Scenario	39.0	0.0	27.7	66.7	1.1

2	Model Results: 2BCTs Total One-Way Travel Time in Minutes (Har-Com1)	Total One-Way Travel Time in Minutes (Com1-BCT)	Total One-Way Travel Time in Minutes (BCT-Market)	Total Travel Time in Minutes	Total Travel Time in Hours
L1, Scenario 3	23.8	0.0	35.8	59.6	1.0
L2, Scenario 4	37.9	25.7	35.4	98.9	1.6
L2, Scenario 5	30.5	30.6	30.2	91.4	1.5
L2, Scenario 6	35.1	32.3	34.5	101.9	1.7

	Model Results: 5BCTs Total One-Way Travel Time in Minutes (Har-Com1)	Total One-Way Travel Time in Minutes (Com1-BCT)	Total One-Way Travel Time in Minutes (BCT-Market)	Total Travel Time in Minutes	Total Travel Time in Hours
L1, Scenario 1	27791.5	0.0	188.7	27980.2	466.3
L1, Scenario 2	16691.4	0.0	196.0	16887.3	281.5
L1, Scenario 3	30596.5	0.0	207.6	30804.1	513.4
L2, Scenario 4	62821.1	2216.2	191.0	65228.4	1087.1
L2, Scenario 5	60999.5	3314.2	177.1	64490.9	1074.8

	Model Results: 5BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L2, Scenario 6	72649.8	3110.1	197.2	75957.2	1266.0
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	36.6	0.0	37.7	74.4	1.2
L1, Scenario 2	30.4	0.0	39.2	69.6	1.2
L1, Scenario 3	23.8	0.0	41.5	65.3	1.1
L2, Scenario 4	30.1	22.2	38.2	90.4	1.5
L2, Scenario 5	29.2	33.1	35.4	97.8	1.6
L2, Scenario 6	31.0	31.1	39.4	101.5	1.7

	Model Results: 10BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L1, Scenario 1	51948.9	0.0	401.4	52350.4	872.5
L1, Scenario 2	31525.6	0.0	412.2	31937.8	532.3
L1, Scenario 3	29806.7	0.0	447.5	30254.2	504.2
L2, Scenario 4	112855.8	5002.0	431.9	118289.7	1971.5
L2, Scenario 5	29722.7	6602.7	407.2	36732.6	612.2
L2, Scenario 6	65336.7	4935.2	402.3	70674.1	1177.9
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	35.7	0.0	40.1	75.8	1.3
L1, Scenario 2	31.7	0.0	41.2	73.0	1.2
L1, Scenario 3	30.5	0.0	44.7	75.2	1.3
L2, Scenario 4	37.1	25.0	43.2	105.3	1.8
L2, Scenario 5	23.7	33.0	40.7	97.5	1.6
L2, Scenario 6	30.5	24.7	40.2	95.4	1.6

	Model Results: 15BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L1, Scenario 1	78056.2	0.0	626.4	78682.7	1311.4
L1, Scenario 2	43104.2	0.0	649.8	43754.1	729.2
L1, Scenario 3	43384.9	0.0	669.0	44053.9	734.2
L2, Scenario 4	35360.7	7984.0	649.9	43994.7	733.2
L2, Scenario 5	70848.6	10364.3	643.2	81856.1	1364.3
L2, Scenario 6	95521.8	8316.8	656.2	104494.8	1741.6
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	35.9	0.0	41.8	77.6	1.3
L1, Scenario 2	32.1	0.0	43.3	75.4	1.3
L1, Scenario 3	30.6	0.0	44.6	75.2	1.3
L2, Scenario 4	24.7	26.6	43.3	94.7	1.6
L2, Scenario 5	31.6	34.5	42.9	109.1	1.8
L2, Scenario 6	35.2	27.7	43.7	106.7	1.8

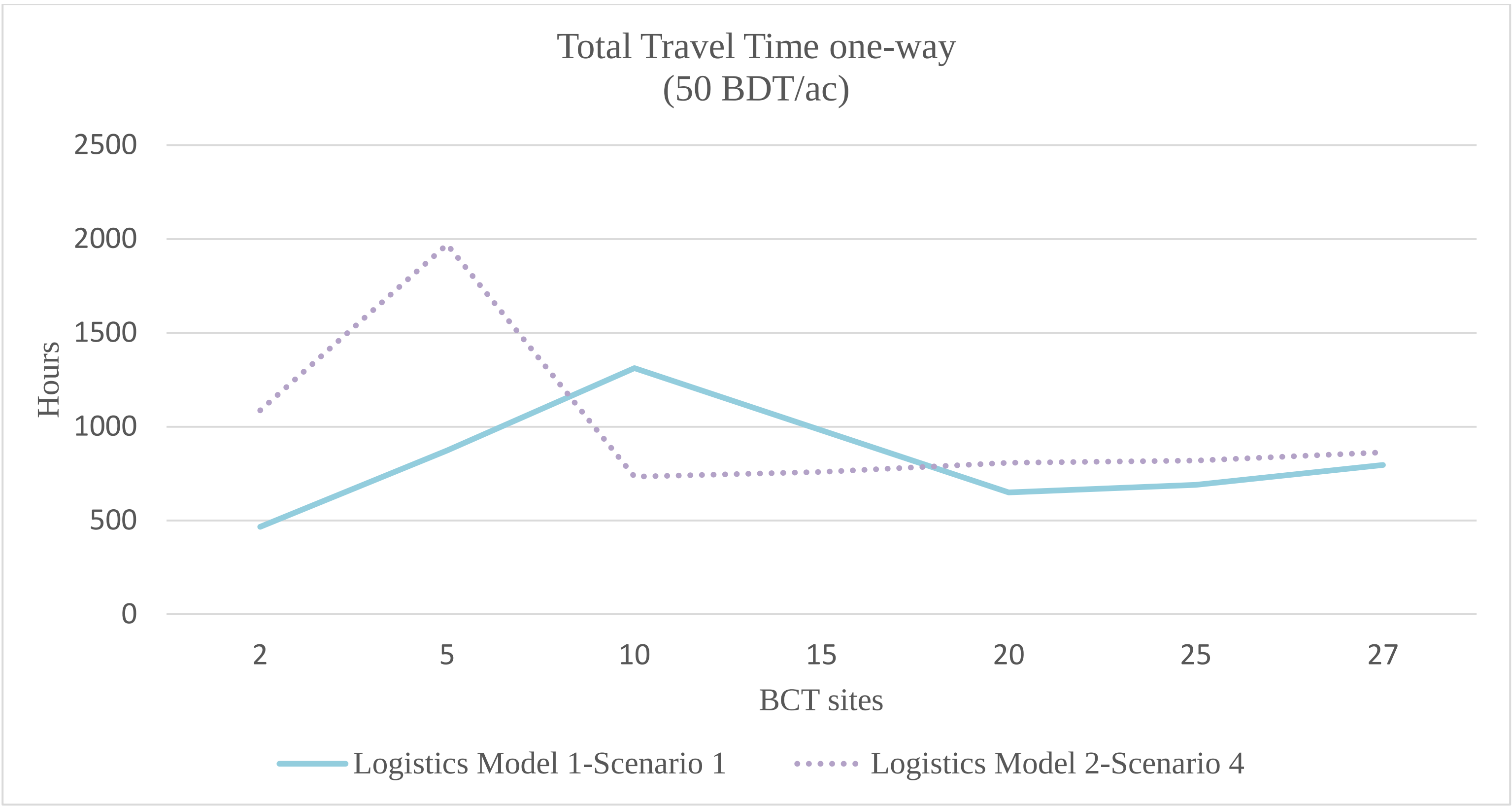
	Model Results: 20BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	Total One-Way Travel Time in Minutes (Com1-BCT)	Total One-Way Travel Time in Minutes (BCT-Market)	Total Travel Time in Minutes	Total Travel Time in Hours
L1, Scenario 1	57931.1	0.0	908.5	58839.6	980.7
L1, Scenario 2	30596.5	0.0	938.2	31534.7	525.6
L1, Scenario 3	56469.7	0.0	929.2	57398.9	956.6
L2, Scenario 4	31666.0	12979.7	861.9	45507.5	758.5
L2, Scenario 5	68535.9	14439.1	910.6	83885.6	1398.1
L2, Scenario 6	95521.8	13473.2	867.3	109862.3	1831.0
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	30.1	0.0	45.4	75.5	1.3
L1, Scenario 2	23.8	0.0	46.9	70.7	1.2
L1, Scenario 3	30.8	0.0	46.5	77.3	1.3
L2, Scenario 4	23.8	32.4	43.1	99.4	1.7
L2, Scenario 5	31.3	36.1	45.5	112.9	1.9
L2, Scenario 6	35.2	33.7	43.4	112.3	1.9

	Model Results: 25BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L1, Scenario 1	37867	0	1122	38990	650
L1, Scenario 2	39291	0	1202	40493	675
L1, Scenario 3	87503	0	1228	88731	1479
L2, Scenario 4	30657	16699	1050	48406	807
L2, Scenario 5	32288	17110	1106	50504	842
L2, Scenario 6	49409	17716	1107	68232	1137
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	24.3	0.0	44.9	69	1.2
L1, Scenario 2	23.7	0.0	48.1	72	1.2
L1, Scenario 3	31.4	0.0	49.1	81	1.3
L2, Scenario 4	24.4	33.4	42.0	100	1.7
L2, Scenario 5	24.0	34.2	44.2	102	1.7
L2, Scenario 6	28.7	35.4	44.3	108	1.8

	Model Results: 27BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L1, Scenario 1	40146	0	1216	41362	689
L1, Scenario 2	43165	0	1297	44462	741
L1, Scenario 3	66689	0	1325	68014	1134
L2, Scenario 4	29572	18407	1133	49112	819
L2, Scenario 5	31402	19055	1191	51648	861
L2, Scenario 6	49715	19130	1203	70048	1167
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	24.1	0.0	45.0	69	1.2
L1, Scenario 2	23.7	0.0	48.0	72	1.2
L1, Scenario 3	27.9	0.0	49.1	77	1.3
L2, Scenario 4	24.5	34.1	42.0	101	1.7
L2, Scenario 5	23.9	35.3	44.1	103	1.7
L2, Scenario 6	28.8	35.4	44.5	109	1.8

	Model Results: 30BCTs				
	Total One-Way Travel Time in Minutes (Har-Com1)	**Total One-Way Travel Time in Minutes (Com1-BCT)**	**Total One-Way Travel Time in Minutes (BCT-Market)**	**Total Travel Time in Minutes**	**Total Travel Time in Hours**
L1, Scenario 1	46356	0	1344	47700	795
L1, Scenario 2	46041	0	1429	47470	791
L1, Scenario 3	74592	0	1509	76102	1268
L2, Scenario 4	29572	20931	1272	51775	863
L2, Scenario 5	30504	21220	1326	53050	884
L2, Scenario 6	49922	20990	1348	72260	1204
	Average Travel Time in Minutes (Har-Com1)	**Average Travel Time in Minutes (Com-BCT)**	**Average Travel Time in Minutes (BCT-Market)**	**Total Average Travel Time in Minutes**	**Total Average Travel Time in Hours**
L1, Scenario 1	24.3	0.0	44.8	69	1.2
L1, Scenario 2	23.8	0.0	47.6	71	1.2
L1, Scenario 3	27.5	0.0	50.3	78	1.3
L2, Scenario 4	24.5	34.9	42.4	102	1.7
L2, Scenario 5	24.0	35.4	44.2	104	1.7
L2, Scenario 6	28.8	35.0	44.9	109	1.8

APPENDIX B


Total Travel Time one-way
(50 BDT/ac)
Hours
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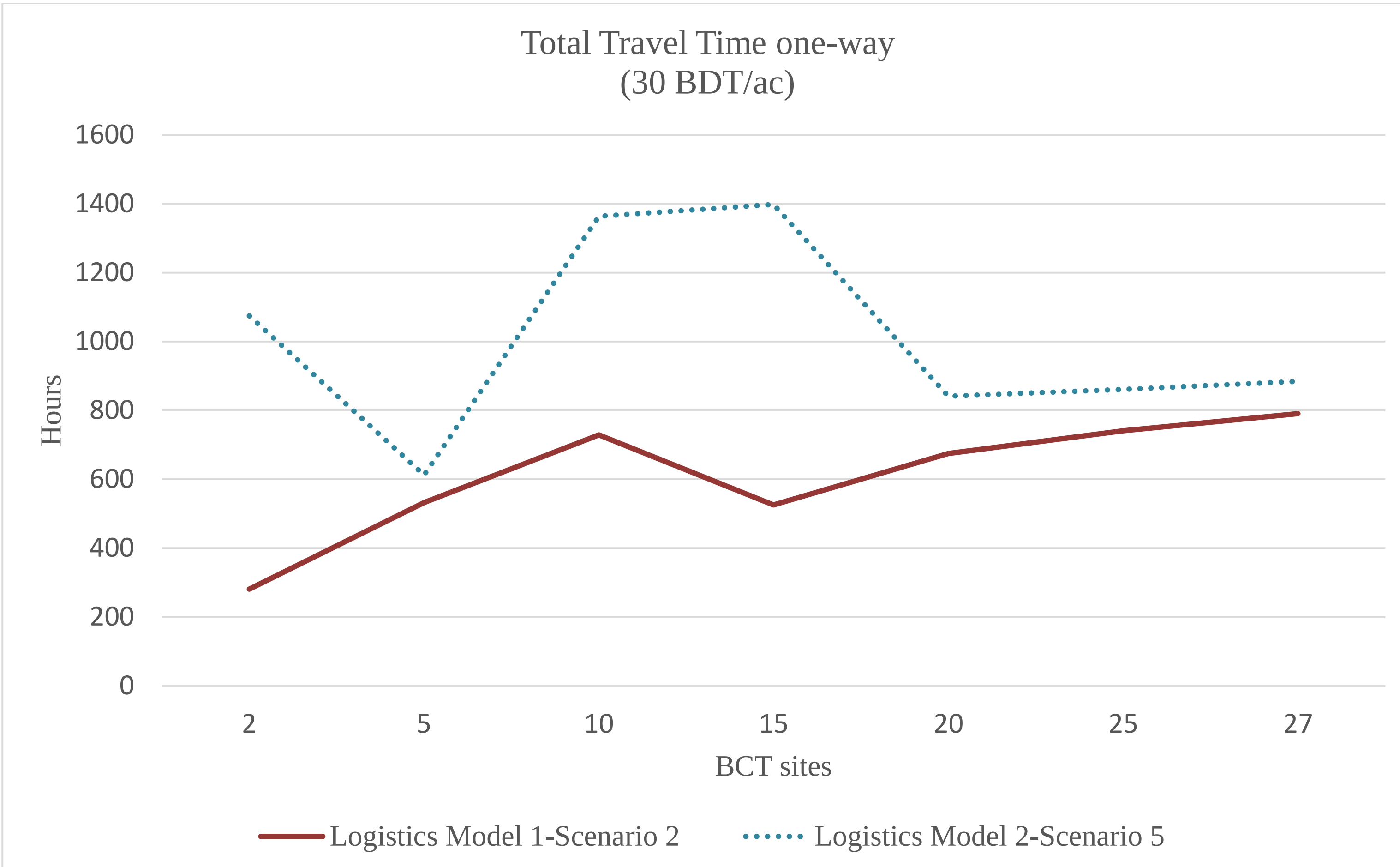
2000
1500
1000
500
0
2
5
10
15
20
25
27
BCT sites
Logistics Model 1-Scenario 1
Logistics Model 2-Scenario 4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(30 BDT/ac)
Hours
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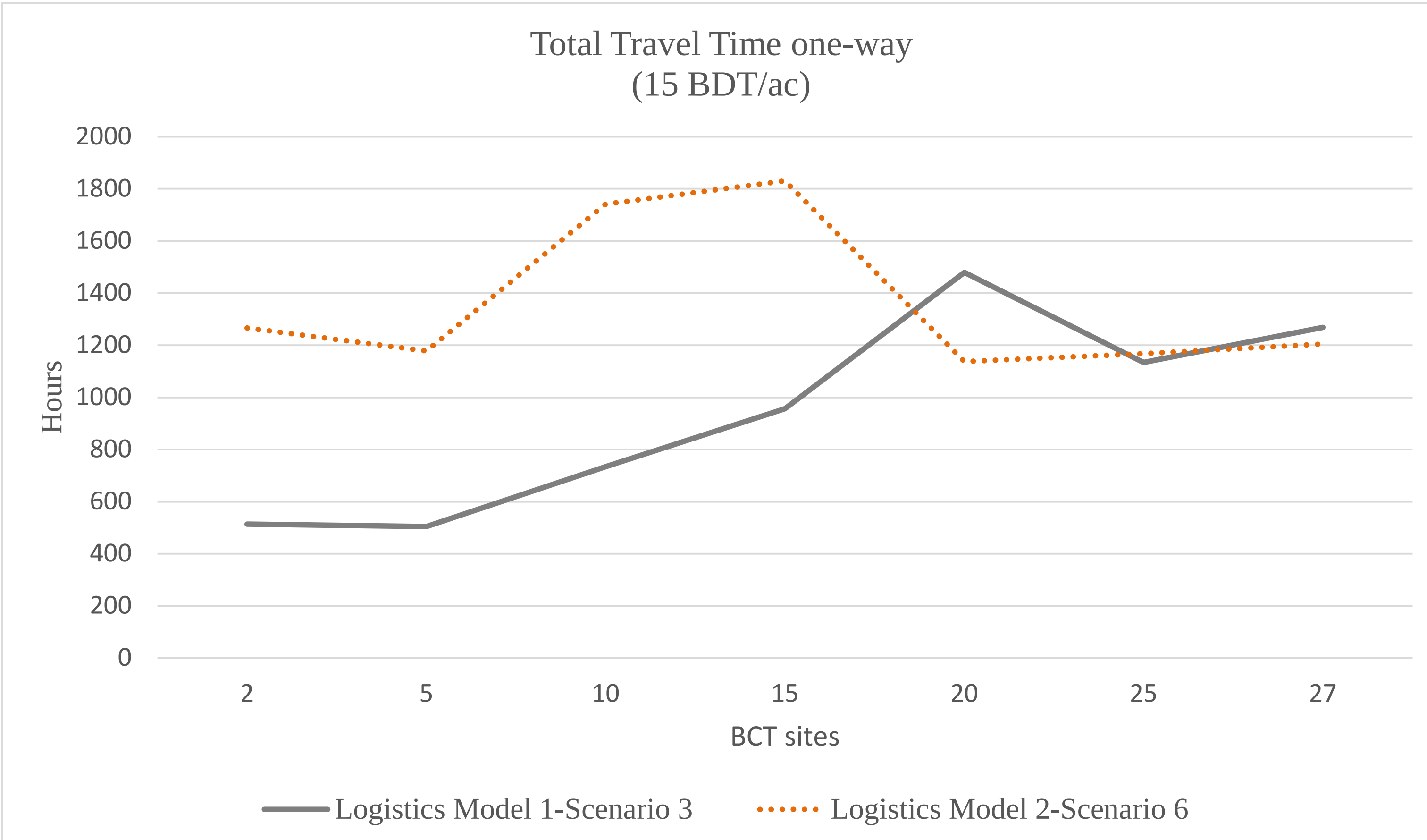
1400
1200
1000
800
600
400
200
0
2
5
10
15
20
25
27
BCT sites
Logistics Model 1-Scenario 2
Logistics Model 2-Scenario 5



Total Travel Time one-way
(15 BDT/ac)
Hours
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2
5
10
15
20
25
27
BCT sites
Logistics Model 1-Scenario 3
Logistics Model 2-Scenario 6