BIOREFINERY NETOWRK DESIGN UNDER UNCERTAINTY

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Korin Reid

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BIOREFINERY NETWORK DESIGN UNDER UNCERTAINTY

Approved by:

Dr. Matthew Realff, Advisor
School of Chemial and Biomolecular Engineering
Georgia Institute of Technology

Dr. Steven French
School of City and Regional Planning
Georgia Institute of Technology

Dr. Athanasios Nenes
School of Chemial and Biomolecular Engineering
Georgia Institute of Technology

Dr. Valerie Thomas
School of Industrial and Systems Engineering
Georgia Institute of Technology

Dr. Yoshiaki Kawajiri
Chemical and Biomolecular Engineering
Georgia Institute of Technology

Date Approved: May 2015

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LIST OF ABBREVIATIONS

GIS	Geographic Information Systems
MILP	Mixed Integer Linear Programming
FT	Fisher Tropsch
RNFA	Reaction network flux analysis
NASS	National Agricultural Statistics Service
NCEP	National Center for Environmental Prediction
NLDAS	NASA Land Data Assimilation Systems
NARR	North American Regional Reanalysis
WRF	Weather Research Forecast
ORNL	Oakridge National Labs
MMNET	Multi Modal Transportation Network
NRCS	*N*atural Resources Conservation Service
PRISM	Parameter-elevation Regressions on Independent Slopes Model
STATSGO	States Soil Geographic Database
EPIC	Environmental Policy Integrated Climate
ALMANAC	Agricultural Land Management Alternatives with Numerical Assessment Criteria
NCDC	National Climatic Data Association
COP	Cooperative Observer Program
APEX	Agricultural Policy/Environmental EXtender
POLYSYS	Policy Analysis System
WGEN	Weather Generator
DISC	Data Information Services Center

DNDC	DeNitrification-DeComposition
SWAT	Soil and Water Assessment Tool
DAYCENT	Daily Century Model
DAYMET	Daily Surface Weather and Meteorological Summaries
USDA	US Department of Agriculture
LAI	Leaf Area Index
MAXLAI	Maximum Leaf Area Index
RLAI	Relative Leaf Area Index
FHUM	Fraction of Heat Units to Maturity
HUM	Heat Units to Maturity
AGI	Annual Growth Initiation
PAR	Photosynthetically Active Radiation
RUE	Radiation Use Efficiency
MAD	Median Absolute Deviation

SUMMARY

This work integrates perennial feedstock yield modeling using climate model data from current and future climate scenarios, land use datasets, transportation network data sets, Geographic Information Systems (GIS) tools, and Mixed integer linear programming (MILP) optimization models to examine biorefinery network designs in the southeastern United States from an overall systems perspective. Both deterministic and stochastic cases are modeled. Findings indicate that the high transportation costs incurred by biorefinery networks resulting from the need to transport harvested biomass from harvest location to processing facilities can be mitigated by performing initial processing steps in small scale mobile units at the cost of increased unit production costs associated with operating at smaller scales.

Indeed, it can be financially advantageous to move the processing units instead of the harvested biomass, particularly when considering a 10-year planning period (typical switchgrass stand life). In this case, the mobile processing supply chain configuration provides added flexibility to respond to year-to-year variation in the geographic distribution of switchgrass yields. In order to capture the effects of variation in switchgrass yields and incorporate it in optimization models, yield modeling was conducted for both current and future climate scenarios. (In general profits are lower in future climate scenarios). Thus, both the effects of annual variation in weather patterns and varying climate scenarios on optimization model decisions can be observed.

CHAPTER 1 INTRODUCTION

The Energy Independence and Security ACT (EISA 2007) states that by 2020, 36 billion gallons of biofuels should be consumed as part of the US liquid fuel demand. Of these 36 billion gallons, 21 billion should be cellulosic biofuel, biomass based diesel, or other forms of advanced biofuels. In order to meet biofuel feedstock demands, large volumes of biomass will be required. According to the Billion Ton study conducted by The US Department of Energy, (Perlack, Wright et al. 2005, Perlack and Stokes 2011) 20 to 60 million acres of land (depending on projected yields) in the US must be converted to energy crop production in order to meet EISA mandates. The wide range in the reported land use change estimates suggests that variations in annual crop yield, as well as process efficiency, could play an important role in biorefinery network design, planning and scheduling. Thus, land and atmospheric conditions, which affect yearly crop yield, will need to be considered in biorefinery system design. The drought conditions experienced repeatedly in different parts of the U.S., most recently in the Midwest in 2012 and the Southeast in 2008, and the subsequent agricultural supply chain interruptions that ensued point to the importance of understanding whether spatial-temporal variations in yields will have a strong influence on biorefinery network design.

In addition to the temporal variations in biofuel crop yield, spatial variations in crop yields also contribute to the complexity of the biorefinery design problem. In fact, the spatial distribution of biofuel feedstock introduces a very important tradeoff between various processing facility size decisions. Traditionally, biorefinery optimization models that address this tradeoff have focused on determining the optimal biorefinery size and location. A great benefit of constructing a large centrally located biorefinery is economies of scale. However, in order to satisfy feedstock demands for a large facility, biomass must travel potentially large distances from farmgate to biorefinery locations for processing, resulting in large transportation costs. One possible solution for the reduction of transportation costs is the construction of smaller geographically distributed facilities. Unfortunately, this solution comes at the expense of economies of scale. Smaller more distributed facilities incur higher fixed production costs, but benefit from decreased transportation costs as biomass is transported shorter distances. As a compromise, one might consider performing an initial processing step using transportable processing units that move to the farmgate location, thus transporting a denser feedstock at reduced expense. Final processing of feedstock can then be conducted at a large centralized facility so as to benefit from economies of scale and reduced handling costs.

A possible initial processing step that could be conducted at biomass harvest locations using smaller scale mobile processors is the thermochemical conversion of biomass to crude bio-oil via fast pyrolysis. By moving the processing units instead of the biomass for this initial processing step, the transportation cost reductions of distributed processing supply chains (specifically by transporting liquid bio-oil instead of less energy dense and solid biomass feedstock) are realized. The bio-oil produced can be upgraded for future use in transportation fuels. The upgrading steps have the potential to be implemented within existing petroleum industry infrastructure whereby the economies of scale benefits of large centralized facilities are realized.

In chapter 2, two deterministic MILP optimization models with economic objective functions are presented. One such model represents the case in which initial processing steps take place at fixed stationary processing facilities (harvested biomass is transported), while the other model explores the possibility of conducting initial processing steps at the harvest location using smaller scale mobile units. Both model formulations use the resource and state task network representation found in Pantelides, Realff et al. (1995) and Kondili, Pantelides et al. (1993). The case studies presented here consider a biorefinery network in the southeastern United States with switchgrass as the model perennial energy crop, but the framework is very general and could be easily extended to study other crops and regions of interest.

To explore the impact of varying weather patterns on biorefinery network performance, spatial and temporal variations in crop yield are represented in this formulation. Available cropland acres for the region of study are estimated using spatially explicit land use datasets. In addition, gridded climate model output data from current and future climate scenarios are used to predict switchgrass yields for particular years of interest. The analysis in chapter 2 includes deterministic optimization model results using switchgrass yield predictions based on climate model output data from both current and future climate scenarios. The details of the switchgrass yield modeling effort are outlined in chapter 3. Finally, in chapter 4 the optimization modeling effort is revisited in order to examine the effects of uncertainty in crop yield. Specifically, in the context of chapter 4, the optimization models introduced in chapter 2 are posed as two stage stochastic problems.

CHAPTER 2 DETERMINISTIC OPTIMIZATION MODEL

LITERATURE REVIEW

There are numerous studies in the literature that present optimization models for the biorefinery supply chain problem. Studies vary significantly in where they choose to place their emphasis, and hence modeling effort, depending on the goals of the analysis. Broadly the literature can be classified into process route selection, process synthesis and design, and supply chain design.

The emphasis of the process route selection literature is to screen large sets of potential feedstocks, processes, and final fuel molecules to make optimal choices between routes. Nica, Parts et al. (2011) formulate a MILP to determine production routes for ethanol, butanol, succinic acid, gasoline, and gasohol from lignocellulosic biomass and crude oil. The case study presented considered 72 processing steps, and examined several objectives including product yield maximization, chemical cost minimization, waste minimization, and minimization of fixed equipment costs. Objective space plots are presented in order to demonstrate the tradeoffs among the various objectives. Although conversion technology options are modeled in detail, feedstock logistics are not represented. Voll and Marquardt (2012) use a reaction network flux analysis (RFNA) method in order to determine the best production pathways for biomass processing. Ponce-Ortega, Pham et al. (2012) use a disjunctive programming formulation to select pathways from biomass to biochemicals and fuels that considers a large number of possible process alternatives. The process parameters are either optimized simultaneously with the process pathway selection or sequentially to improve the computational performance.

In the process synthesis and design area there have been efforts to improve the energy and water efficiency of processes to convert specific biomass sources into different fuel types. This is for both thermochemical and biochemical processes, examples of this include (Ahmetovic, Martin et al. 2010, Martin and Grossmann 2011, Martin and Grossmann 2011, Martin and Grossmann 2011, Martin and Grossmann 2012, Baliban, Elia et al. 2013, Gebreslassie, Slivinsky et al. 2013). In these cases the focus is on the process technology choices and optimization of water and energy and not the overall supply chain optimization or feedstock selection or variability.

Sharma, Sarker et al. (2011) formulate a MILP with an overall economic objective to determine raw material selection, product and technology selections, sales forecast, utility integration, emission estimates, and financial decisions such as debt and equity mix. The lignocellulosic feedstocks considered are corn stover, wheat straw, switchgrass, and miscanthus; lipid feedstocks are also considered. The biomass procurement costs were generated from a uniform distribution using cost estimates found in literature. The model assumed that a certain fixed acreage of land would be available for cellulosic feedstock. Additionally, both biochemical and thermochemical conversion technologies are considered. This study employs an objective function that seeks to maximize stakeholder value over a 12 year planning horizon. Crop yields for the various feedstocks are considered, but are assumed to be constant over the planning horizon. The case study includes two potential lipid suppliers, and three potential lignocellulosic biomass suppliers. While the model does begin to consider feedstock logistics, a small area is considered (five hypothetical suppliers are modeled), and it does not make use of empirical data sets.

There have been several recent studies that focus on the multi-objective nature of biomass to fuel systems. Tan, Ballacillo et al. (2009) propose a fuzzy optimization formulation that employs biodiesel and ethanol production targets in addition to usage limits on land, water, and CO2 emissions. The agricultural resources considered in the case study presented are coconut, corn, and sugarcane. Kasivisvanathan, Ng et al. (2012) also present a multiobjective biorefinery problem; in this case, a fuzzy optimziation solution approach is employed to solve a palm-oil biorefinery problem. Pareto analysis, and a sensitiviy study are conducted as part of this production pathway study. Shabbir, Tay et al. (2012) uses a fuzzy optimization appraoch to examine economic and environmental objectives simultaneously. Gebreslassie, Yao et al. (2012), present a stochastic programming model for a biorefinery supply chain under uncertainty for the state of Illinois. A multi-cut L shaped method is used to solve a multiobjective program in which annualized cost and risk minimization are considered simultaneously.

Process system engineering studies that focus more explicitly on decisions around locating facilities, as opposed to synthesizing the technologies, have also become prevalent in recent years following the early work of Sperling (1984) and Jenkins (1997). A facility location approach to the biorefinery problem is considered by Aksoy, Cullinan et al. (2008).   Specifically, this model seeks to determine the optimal refinery location such that transportation costs are minimized. In this model, the biomass source is poultry litter. Two case studies are presented in this paper: a twelve county study, and a twenty-four county study. County level poultry litter availability data are estimated from county level broiler production data. Important conclusions are that the availability of feedstock is a critical determining factor in transportation costs. Decreases in feedstock availability results in large increases in transportation costs.

A spatially explicit model of bioethanol supply chain design in Northern Italy is presented in (Zamboni, Bezzo et al. (2009), Zamboni, Shah et al. (2009)). The study divides Northern Italy into a grid of 59 squares, 50x50km, for biomass supply plus one to represent biomass imports from beyond the region. The demand is placed at internal depots where the ethanol is blended to the gasoline stock. The objectives studied included cost and greenhouse gas emission minimization. Leduc, Lundgren et al. (2010) formulate a facility location optimization problem for methanol produced from woody biomass. Three potential plant sizes are considered, and the scope of the facility location problem is a single city with a spatial resolution of one third of a degree. A sensitivity analysis with respect to biomass price, transportation costs, and heating prices and demands is also included in this work. Parker, Tittmann et al. (2010) present a geographic information systems (GIS) feedstock model in addition to a biorefinery optimization model. The model includes a multi-modal transportation system that has optimized pathways between candidate locations for biorefinery infrastructure and different types of biomass supply. Thirty production pathways, 12 feedstock types, and 6 conversion technologies are considered in this study and the network structure allows biomass to be shipped to a biorefinery and then from biorefinery locations to fuel distribution terminals. The goal of the paper is to construct a cost curve that shows the marginal cost of the biofuel as a function of the quantity of biofuel produced for the various scenarios.

Kim, Realff et al. (2011) present a MILP model that determines the optimal number, location, and size of processing plants for woody biomass resources using a profit maximization objective function. Conversion technologies, capacities, biomass feedstock locations, transportation from biomass source to conversion facility, and transportation from conversion facility to final market are also determined. This study considers both centralized and distributed network configurations. In the distributed system, biomass resources are transported to several smaller conversion facilities in which the biomass is converted into an intermediate liquid fuel via fast pyrolysis. The resulting bio-oil can be transported to larger Fisher Tropsch (FT) plants for final processing. The case study presented in this paper uses a realistic data set of biomass resource and transportation costs data for the southeastern United States. For the distributed system, four woody biomass types, 30 potential biomass locations, 29 possible quick pyrolysis processing facilities, 10 potential final processing facilities, and 10 potential final product markets are considered. For the centralized system, only the 10 potential final processing facilities are considered.

Bowling, Ponce-Ortega et al. (2011) also consider the use of distributed facilities for initial processing steps. These facilities, referred to as hubs are used to obtain vegetable oil from oil seed feedstock via hexane extraction. The case study presented in this work includes six potential feedstock locations, two potential centralized facility locations, and two possible locations for feedstock hubs. The optimization model also determines hub size.

Shastri, Hansen et al. (2011) present a switchgrass specific optimization model that focuses on feedstock logistics. In particular, harvesting, packing, detailed storage options, and transportation of switchgrass are considered. In this MILP, harvested biomass can be shipped directly to the refinery, or it can be placed in on-farm open-air storage, on-farm covered storage, or on-farm ensiling; biomass can also be shipped to a centralized storage facility. This model also handles in field transportation, transportation between farms, centralized storage, and transportation between farms and refineries. The case study presented in this work includes 13 counties in southern Illinois. Marvin, Schmidt et al. (2011) present a biofuel supply chain and facility location model spanning nine states in the Midwestern United States. This MILP optimization problem selects from 69 candidate biorefinery locations. In order to predict biomass availability, county level grain production data (barley, corn, oats, spring and winter wheat) was obtained from the National Agricultural Statistics Service *(*NASS). Annual variation in biomass availability is not considered in this study.

You and Wang (2011) present an optimization model in which transportation costs are reduced by combining smaller, distributed pre-conversion facilities with centralized plants for final processing. The technologies considered in this work are biomass gasification followed by Fischer-Tropsch conversion and fast pyrolysis followed by hydroprocessing. The study includes the presentation of pareto-optimal curves that consider two objectives: cost minimization and greenhouse gas (GHG) emission reduction. Their work incorporates biomass moisture content, storage loss, multimodal transportation, geographical availability, and supply seasonality. In You and Wang (2011)several forms of biomass are considered (crop residues, energy crops, and forest residues); however biomass yield is assumed to be constant at 5 tons per acre regardless of geographical location, and feedstock type, unlike the model presented in this thesis which represents spatially explicit crop yield. You and Wang present a case study that includes 99 counties in the state of Iowa, whereas the model presented here has a broader geographical scope of 1908 locations in the Southeastern United States.

OPTIMIZATION MODEL DESCRIPTION

In the case study presented here, both mobile and centralized processing system designs are explored. The supply chain includes eight pipeline accessible terminal locations, and 1908 potential biomass harvest locations. For the fixed processing case, each of the potential biomass harvest locations also serve as candidate biorefineries. Biomass is transported from selected harvest locations to one of the selected candidate biorefinery locations, where biomass is converted into bio-oil via fast pyrolysis. Crude bio oil produced in the vicinity of the pipeline accessible biorefinery locations is transported via oil pipeline to a facility capable of converting the crude bio-oil into a transportation grade fuel. Pyrolysis oil produced at a biorefinery location that is not in the vicinity of a pipeline accessible terminal is first transported by truck to a pipeline accessible terminal from which it is transported via pipeline to final processing facility. In contrast, the mobile processing system design includes mobile units that are transported between potential harvest locations. Fast pyrolysis is conducted at the harvest locations, and the resulting pyrolysis oil is shipped to the nearest pipeline accessible oil terminal locations by truck (if processing site isn’t in the vicinity of a pipeline accessible terminals). Finally, bio-oil is transported via pipeline for final processing as in the centralized processing case.

Decisions for both models include when and where planting, harvesting, and processing tasks should occur. Dry matter losses during infield storage are also modeled. Additionally, annual crop yield, a function of local land and atmospheric conditions is modeled and used as input to the optimization model. For the mobile processing case, mobile unit vehicle routing and mobile unit purchases are also addressed. For the fixed processing case, model decisions include the optimal size and location of processing facilities.

OPTIMIZATION MODEL FORMULATION

Table 2-1 Optimization Model Indices

i	Network locations
k	Resource
p	Task
a	Maximum harvest scenario
t	Time (months)
c	Weather year scenarios
f	Set of final processing Locations

Table 2-2 Optimization Model Sets

P_k	Set of tasks *p* that produce resource *k*
$\overline{P_k}$	Set of tasks *p* that consume resource *k*
H_t	Set of time periods that define the current harvest season as observed in period *t*
J_k	Set of incoming transfer tasks
$\overline{J_k}$	Set of outgoing transfer tasks
L	Set of pipeline accessible harvest locations
R	Set of non pipeline accessible harvest locations
F	Set of locations at which final processing takes place

Table 2-3 Resources

k_1	Planted Land
k_2	Harvested Switchgrass
k_3	Pyrolysis Oil
k_4	Char Byproduct
k_5	Gas Byproduct
k_6	Small Mobile Unit
$\overline{k_6}$	Small Mobile Unit Before Startup
$\overline{\overline{k_6}}$	Small Mobile Unit After Startup
k_7	Medium Mobile Unit
$\overline{k_7}$	Medium Mobile Unit Before Setup
$\overline{\overline{k_7}}$	Medium Mobile Unit After Setup

Table 2-4 Tasks

p_1	Plant Switchgrass
p_2	Harvest Switchgrass
p_3	Start Process Small Mobile Unit
p_4	Start Process Medium Mobile Unit
p_5	Process Small Mobile Unit
p_6	Process Medium Mobile Unit
p_7	Wait Small Mobile Unit
p_8	Wait Medium Mobile Unit
p_{9-12}	Process Centralized

Table 2-5 Optimization Model Variables

B_{ipt}	Extent of task *p* that starts at location *i* in time *t*
S_{ikt}	The amount of material *k* that is stored at location *i* in time *t*
N_{ipt}	Number of integer resources that start task *p* at location *i* at time period *t*
$N_{i'ikt}$	Number of mobile resource of type *k* that begin moving from location *i'* to location *i* at time *t*
$M_{i'ikt}$	Quantity of resource *k* that is transported from location i' to location *i* at time *t*
S_{ikt}	Amount of resource *k* at location *i* as observed in time period *t*
N_{ikt}	Number of integer resource *k* at location *i* as observed in time period *t*
N_k^T	Total number of integer resource k
W_{ip}	Binary variable that signifies the existence of a biorefinery capable of executing task *p* at candidate refinery location *i*
V_{ip}	Per unit revenue generated from the execution of task *p* at location *i*
NPV	Net present value of the project over the planning horizon

Table 2-6 Optimization Model Parameters

SL_k	Storage loss associated with storing resource *k* for one time period
β_i	Available cropland acres at location *i*
Y_{ikc}	Yield of crop *k* at location *i* under crop yield scenario *c*
ρ_{ipkt}	Amount of resource *k* produced at location *i* per instance of task *p* at time *t*
$\tau_{i'ik}$	Time required for resource *k* to travel across arc *i'i*
$\tau_p/\overline{\tau_p}$	Time required for task *p* to produce/consume material
Max_p	Capacity of task *p*
Max_{pa}	Capacity of task *p* under maximum planting fraction scenario *a*
Max_k	Capacity/Maximum Quantity of resource k
$\mathrm{Max}_{\mathrm{i'i}}$	Flow capacity on arc $\mathrm{i'i}$
$\mathrm{D}_{\mathrm{i'i}}$	Distance from location *i'* to location *i*
$CV_{i'ik}$	Variable cost associated with transporting resource *k* from location *i'* to location *i*
CF_k	Fixed cost of equipment associated with the production of resource k
CV_p	Variable Cost associated with the execution of task *p*
CV_{ilk}	Variable Transportation Costs associated with transporting resource *k* from location *i* to its corresponding pipeline terminal *l*
CV_{lrk}	Variable Transportation Costs associated with transporting resource *k* from pipeline location *l* to refinery *r*
VE_k	Value of product *k*
YP_k	Percent Yield of resource *k* (dry input basis)

Table 2-7 Optimization Model Parameter Values

L_{k_2}	0.83% per month (Sokhansanj, Mani et al. 2009)
β_i	Determined by cropland database (acres)
Y_{ik_2c}	Yield of crop k_2 at location *i* under crop yield scenario *c*, generated by applying spatially explicit switchgrass crop yield model at location *i*, using land and atmospheric conditions from weather year *c*
$\rho_{i\bar{p}kt}$	1 for all tasks
$\rho_{ip_1k_1t}$	1
$\rho_{ip_2k_2t}$	The product of $\mathrm{Y}_{\mathrm{ik_2c}}$ and β_i adjusted for each time period t based on switchgrass seasonality; expressed in tons
$\rho_{ip_{3-6}k_3t};\ \rho_{ip_{9-12}k_3t}$	0.8 (Kim, Realff, Lee 2011)
$\rho_{ip_{3-6}k_4t};\ \rho_{ip_{9-12}k_4t}$	0.1(Kim, Realff, Lee 2011)
$\rho_{ip_{3-6}k_5t};\ \rho_{ip_{9-12}k_5t}$	0.1(Kim, Realff, Lee 2011)
$\tau_{i'ik}$	0
$\tau_{p_1}/\overline{\tau_{p_1}}$	12/120
$\tau_p/\overline{\tau_p}$	1/0 for tasks $\{\mathrm{p}_{2-}\mathrm{p}_{14}\}$
Max_{p_5}	1500 tons per month (adjusted from Badger 2011)
Max_{p_6}	3000 tons per month (Badger 2011)
Max_{p_3}	2600 tons per month (Badger 2011 adjusted for setup time according to Polagye, Hodgson, eta al. 2007)
Max_{p_4}	1300 tons per month (Badger 2011 adjusted for setup time according to Polagye, Hodgson, eta al. 2007)
$Max_{p_{9-12}}$	1.2 Million – 4.9 Million tons per year (Kim, Realff, Lee 2011)
$Max_{k_1a_1}$	1%-20% of available cropland depending on scenario
$Max_{i'i}$	Equals 1 if distance between location pairs is less than 100 miles; Calculated in ArcMap using Multimodal Transportation Network Dataset (MMNET)
$Max_{\bar{\bar{k}}_{6\ldots7}}$	0
$D_{i'i}$	Calculated in ArcMap using MMNET Dataset
$CV_{i'ik}\ \forall\ k \in K_m$	(\$/mile) Calculated using $D_{i'i}$ and parameters from Polagye, Hodgson et al. 2007
$CF_{k_{6-9}}$	From Badger 2011, adjusted using for 0.6 scale factor
$CV_{i'ik_{3-6}}$	Calculated using $D_{i'i}$ and transportation costs per ton-mile values from (Kim, Lee, Realff 2011)
$CF_{p_{9-12}}$	(\$/year from Kim, Lee, Realff 2011)
$CV_{p_{9-12}}$	(\$/ton from Kim, Lee, Realff 2011)
$CV_{p_{3-6}}$	\$15.6/ton (from mobile unit thermal and electric utility needs from Badger 2011, and grass specific material balance from Kim, Lee, Realff 2011)
VE_{k_3}	\$241.8/ton (Badger et al 2011)
VE_{k_4}	\$40/ton (Kim, Lee, Realff 20111)
VE_{k_5}	\$20/ton (Kim, Lee, Realff 20111)
YP_{k_3}	80% (Kim, Lee, Realff 20111)
YP_{k_4}	10% (Kim, Lee, Realff 20111)
YP_{k_5}	10% (Kim, Lee, Realff 20111)

Table 2-8 Tasks and Resources for Mobile Model

	Producing Task		**Consuming Tasks**		Incoming Transfer Task		Outgoing Transfer Task	
k	$\boldsymbol{P_k}$		$\overline{\boldsymbol{P_k}}$		J_k		$\bar{J}_k$	
k_1	$B_{ip_1 t-120}$	$\forall i, t$	$B_{ip_1 t-1}$	$\forall i, t$				
k_2	$B_{ip_2 t-1}$	$\forall i, t$	$B_{ip_{3-}p_6 t}$	$\forall i, t$				
k_3	$B_{ip_{3-}p_6 t-1}$	$\forall i, t$			$M_{i'ik_3 t}$	$\forall i', i\epsilon(L \cup F),$ $i'\epsilon R, t$	$M_{ii'k_3 t}$	$\forall i, i'\epsilon(L \cup F),$ $i\epsilon R$
k_4	$B_{ip_{3-}p_6 t-1}$	$\forall i, t$						
k_5	$B_{ip_{3-}p_6 t-1}$	$\forall i, t$						
$\overline{k_6}$	$N_{ip_7 t}$	$\forall i, t$	$N_{ip_3 t}$	$\forall i, t$	$N_{i'ik_6 t}$	$\forall i', i$		
$\overline{\overline{k_6}}$	$N_{ip_3 t-1}$ $N_{ip_5 t-1}$	$\forall i, t$	$N_{ip_7 t}$ $N_{ip_5 t}$	$\forall i, t$			$N_{ii'k_6 t}$	$\forall i, i', t$
$\overline{k_7}$	$N_{ip_8 t}$	$\forall i, t$	$N_{ip_4 t}$	$\forall i, t$	$N_{i'ik_7 t}$	$\forall i, i'$		
$\overline{\overline{k_7}}$	$N_{ip_4 t-1}$ $N_{ip_6 t-1}$	$\forall i, t$	$N_{ip_8 t}$ $N_{ip_6 t}$	$\forall i, t$			$N_{ii'k_7 t}$	$\forall i, i', t$

Table 2-9 Tasks and Resources for Fixed Processing Model

	Producing Task		**Consuming Tasks**		Incoming Transfer Task		Outgoing Transfer Task	
k	$\boldsymbol{P_k}$		$\overline{\boldsymbol{P_k}}$		J_k		$\bar{J}_k$	
k_1	$B_{ip_1 t-120}$	$\forall i, t$	$B_{ip_1 t-1}$	$\forall i, t$				
k_2	$B_{ip_2 t-1}$	$\forall i, t$	$B_{ip_{9-}p_{12} t}$	$\forall i, t$	$M_{i'ik_2 t}$	$\forall i, t$	$M_{ii'k_2 t}$	$\forall i, t$
k_3	$B_{ip_{9-}p_{12} t-1}$	$\forall i, t$			$M_{i'ik_3 t}$	$\forall i', i\epsilon(L \cup F),$ $i'\epsilon R, t$	$M_{ii'k_3 t}$	$\forall i, i'\epsilon(L \cup F),$ $i\epsilon R, t$

General Biomass Material Balance

A general form of the biomass material balance equation for continuous resources (similar to that Pantelides, Realff et al. (1995) and Kondili, Pantelides et al. (1993)) will be revisited frequently throughout this model description; it is included below.

Equation 2-1

$$\mathrm{S_{ikt}} = \mathrm{S_{ikt-1}} \times (1 - \mathrm{SL_k}) + \sum_{\mathrm{p \in P_k}} \mathrm{B_{ipt-\tau_p}} \times \rho_{\mathrm{ikpt}} - \sum_{\mathrm{p \in \overline{P_k}}} \mathrm{B_{ipt}} + \sum_{\mathrm{i'}} \mathrm{M_{i'ikt-\tau_k}}$$

$$- \sum_{\mathrm{i'}} \mathrm{M_{ii'kt}} \;\; \forall \mathrm{i}, \mathrm{K} \in \mathrm{k_{1 \ldots 5}}, \mathrm{t}$$

For mobile unit resources, the balance is as follows.

Equation 2-2

$$\mathrm{N}_{\mathrm{i}k\mathrm{t}} = \mathrm{N_{ikt-1}} + \sum_{\mathrm{i'}} \mathrm{N_{i'ik\,t-1}} - \sum_{\mathrm{i'}} \mathrm{N_{ii'k\,t}} + \sum_{\mathrm{p \in P_k}} \mathrm{N_{ip\,t-1}} - \sum_{\mathrm{p \in \overline{P_k}}} \mathrm{N_{ipt}} \;\; \forall \mathrm{i}, \mathrm{K} \in \mathrm{k_{6 \ldots 7}}, \mathrm{t}$$

Equation 2-3

$$\mathrm{S_{ikt}}\,, \mathrm{B_{ipt}}\,, \mathrm{T_{ii'kt}}, \mathrm{N}_{\mathrm{i}k\mathrm{t}} \geq 0 \;\; \forall \mathrm{i'}, \mathrm{i}, \mathrm{k}, \mathrm{p}, \mathrm{t}$$

According to **Equation 2-1**, the amount of continuous resource k at location i as observed in period t equals the amount that was available in the previous time units, less any material lost during storage, plus the net production of material from the execution of tasks, less the net transfer of material. Non-negativity constraints are included also. For the mobile unit balance, the number of mobile unit resources of type k at location i as observed in time period t equals the amount available in previous time periods, plus units that have recently completed task execution, plus net transport of units, less mobile units that begin tasks. A listing of the various resources and tasks used in this problem is provided in **Table 2-3** and **Table 2-4**, while variables, parameters, and parameter values are included in **Table 2-5**, **Table 2-6**, and **Table 2-7** respectively. Finally, the form by which the general material balance is specialized to include relevant tasks and resources for the mobile and fixed processing models is described in **Table 2-8** and
Table 2-9 respectively. A more detailed description of the material balances described in **Table 2-8** and
Table 2-9 as well as some additional equations and constraints that complete the formulation are provided in the sections that follow. In particular, the balances described in **Table 2-8** and
Table 2-9 will be expressed as individual equations and accompanied by a discussion of the system features they represent.

Planted Switchgrass Material Balance

In the planted switchgrass material balance, a planting task is used to produce the planted switchgrass resource. A unique aspect of the planted switchgrass balance is that it demonstrates perennial crop dynamics. According to Equation 2-4, the fraction of available cropland acres at location *i* that has been planted with switchgrass as observed in time period *t* equals the fraction of land that was available at the beginning of the planning period plus any fraction of land that is planted in the current time period, less any previously planted land that is no longer considered to be planted due to stand expiration, which for switchgrass is 120 months, or ten years from date of planting. This general representation can easily be extended to include other perennial crops.

Equation 2-4

$$S_{ik_1t} = S_{ik_1t-1} + B_{ip_1t-12} - B_{ip_1t-120} \; \forall i, t$$

It is unlikely that all of the cropland acres at any particular location could be dedicated to energy crop production exclusively. Thus, the fraction of the cropland in the available cropland dataset that can be utilized for energy crop production is limited by the following equation.

Equation 2-5

$$S_{ik_1t} \leq MAX_{k_1} \;\forall\, i, t$$

So far, only the fraction of available cropland at each location has been described. While this is sufficient to satisfy the land use material balance, the actual quantity of acres these fractions represent is of more interest for the purpose of biorefinery network planning. In order to determine the available cropland acres at each potential harvest location, an available cropland database for the southeastern United States is used. The cropland dataset provides the available cropland acres for Texas, Georgia, Alabama, Arkansas, Louisiana, Oklahoma, Tennessee, North Carolina, South Carolina, and Florida at a 3x3 km grid resolution; it is derived from the 2001 Landsat Landcover Dataset, which was obtained through personal communication with Tony Giarrusso (Geographic Information Systems, Georgia Institute of Technology).

Switchgrass Growth Dynamics

Switchgrass is a perennial crop that produces viable stands for approximately ten years. Prior to the 10 seasons of viable harvests, there is a twelve-month dormancy period in which plots do not produce appreciable yields (Cundiff, Dias et al. 1997). Only cropland that has been planted prior to the twelve-month dormancy period, but no earlier than the life of the stand can be harvested. Additionally, harvesting activities can only be conducted during months that fall within the switchgrass harvest season. These growth dynamics characteristics are modeled in Equation 2-6.

Equation 2-6

$$\sum_{t' \in H_t} B_{ip_2t'} \leq \sum_{t''=t-120}^{t''=t-12} B_{ip_1t''} \ \forall\, i, t$$

The fraction of available cropland that is harvested at location *i* in the most recent harvest window,(H_t), cannot exceed the amount that has been planted no less than 12 months prior, and no greater than 120 months prior. No harvests are possible outside of the harvest window. The most recent harvest window, (H_t) is the set of time periods prior to t, but not prior to $\boldsymbol{t_0}$, where $\boldsymbol{t_0}$ signifies the beginning of the harvest season. For example, the switchgrass growth cycle modeled in this case study allows for harvest in months 9, 10 and 11 of each year, so the beginning of the harvest season, t^0 occurs at month 9 of each year. For example, in time period 22, the most recent harvest window consists of time periods 21, and in time period 24, the most recent harvest window includes time periods 21, 22, and 23. Finally, once the 120-month stand life has elapsed, harvests are no longer possible.

Balance on Harvested Biomass Held in Storage (Mobile Case)

For the mobile processing case, harvested switchgrass is processed by smaller scale mobile pyrolysis processing units.

Equation 2-7

$$S_{ik_2t} = S_{ik_2t-1} \times \left(1 - SL_{k_2}\right) + B_{ip_2t-1} \times \rho_{ip_2k_2t} - \sum_{P \in p_3 \ldots p_6} B_{ipt} \ \forall i, t$$

The amount of harvested switchgrass stored at location *i* (in field storage, net wrapped) as observed in time period t, equals the quantity of biomass already in storage (less dry matter loss), plus biomass newly harvested in the previous time period, less biomass that begins processing in time period *t*. A switchgrass specific crop yield model, which will be discussed in detail in chapter 3, is used to determine the maximum annual crop yield values ($\rho_{ip_2k_2t}$).

SwitchgrassYield Modeling

As part of the switchgrass yield modeling effort, 34 years of switchgrass yields (1979-2012) are projected using spatially explicit land and atmospheric variables at a daily time resolution. The daily weather variables required for the switchgrass crop yield model in this study include daily temperature, downward shortwave solar radiation, and soil moisture. The data product used for this study is the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) dataset. The NARR dataset provides weather model reanalysis data at a spatial resolution of 32 km. In order to consider the potential effects of climate change, projected switchgrass yields for the years 2048-2052 is also produced. The variables required by the yield model for the future climate scenario were obtained from collaborators who used the Weather Research Forecast model (WRF) for their analysis.

While soil moisture data is available in the NARR dataset, the switchgrass yield model used here requires that the fraction of soil available water holding capacity at each grid point be calculated daily. In order to derive the fraction available water holding capacity at each grid point from NARR soil moisture data, the Dunne soil data set was obtained from Oakridge National Labs (ORNL). Using the Dunne soil data set, field capacity, wilting point, and profile available water holding capacity data were interpolated to the 32 km grid used in this study using cubic spline interpolation. The available cropland dataset was also interpolated to a 32 km grid to match the highest resolution of daily reanalysis data that was available; thus the final resolution for the biorefinery network optimization model is a 32 km grid.

While a mechanistic switchgrass yield model is used to project maximum annual crop yield values, switchgrass seasonality is used to determine monthly crop yield values. The switchgrass seasonality parameters used in this model are from (Cundiff, Dias et al. 1997) and are as follows: 100% of maximum annual yields can be achieved by harvesting in October, and 95% of maximum annuals yields can be achieved by harvesting in months September and November; no yields can be achieved in any other months. Switchgrass seasonality, projected maximum annual switchgrass yields, and available cropland acres from the cropland dataset together determine total tons of switchgrass that can be harvested by switchgrass harvest tasks.

It should be noted that switchgrass yield patterns vary from region to region. Thus, the years in which the greatest or least amount of potential biomass can be harvested are not the same for every region. The inherent flexibility of the mobile processing system to respond to such variations is a potential advantage of the mobile processing system design. The 32 year average switchgrass yield for 1979-2012 obtained from the switchgrass model used in this paper in addition to a sample 5 year yield pattern (2008-2012) is pictured in Figure 2-1. This five-year yield pattern can be compared to 2048-2052, which is pictured in Figure 2-2. In both of these figures, yields are pictured by quartiles. The actual yields (Mg/h) corresponding to the ranges pictured in Figure 2-1 and Figure 2-2 are outlined in Table 2-10. Figure 2-3 includes the distribution of available cropland acres.

Figure 2-1 Crop Yields in Southeastern United States (1978-2012)

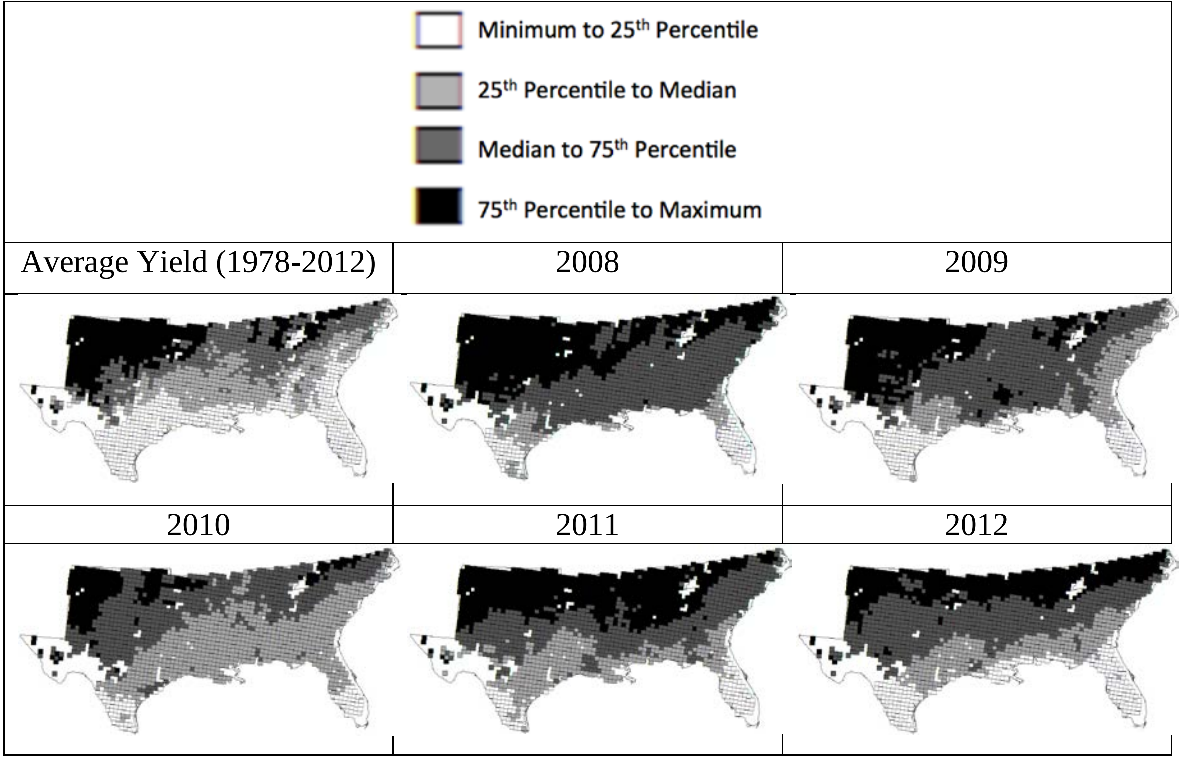
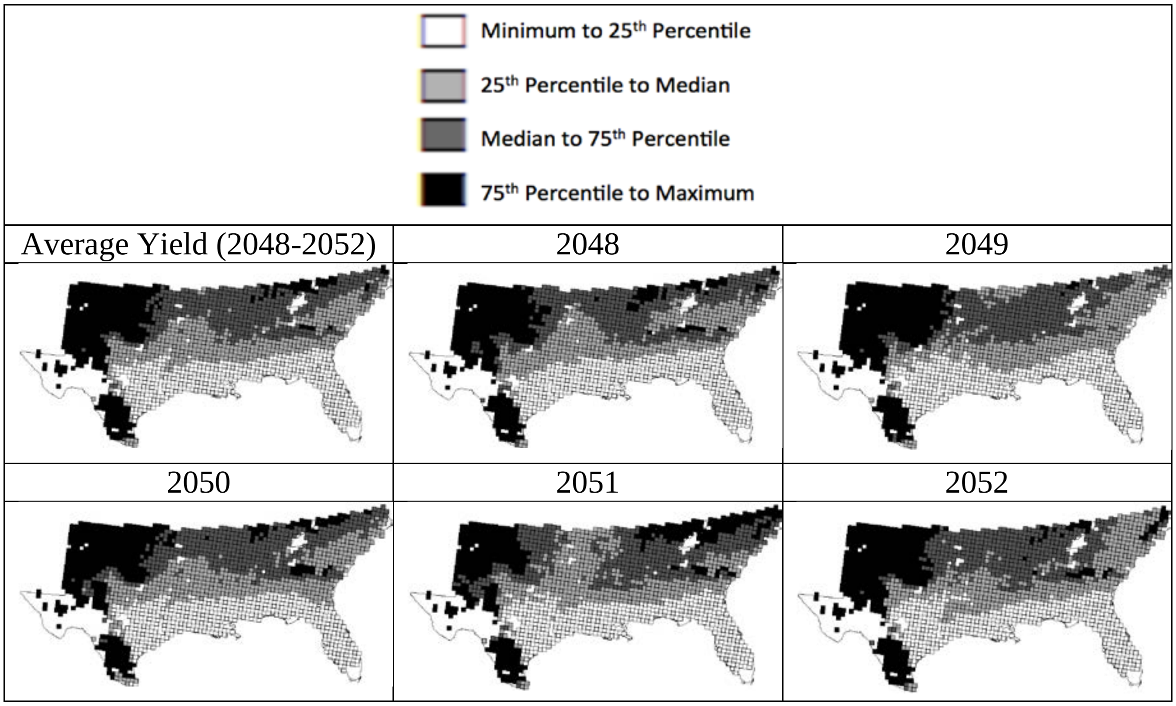


Figure 2-2 Crop Yields in Southeastern United States (2048-2052)



Average Yield (2048-2052)

2048

2049

2050

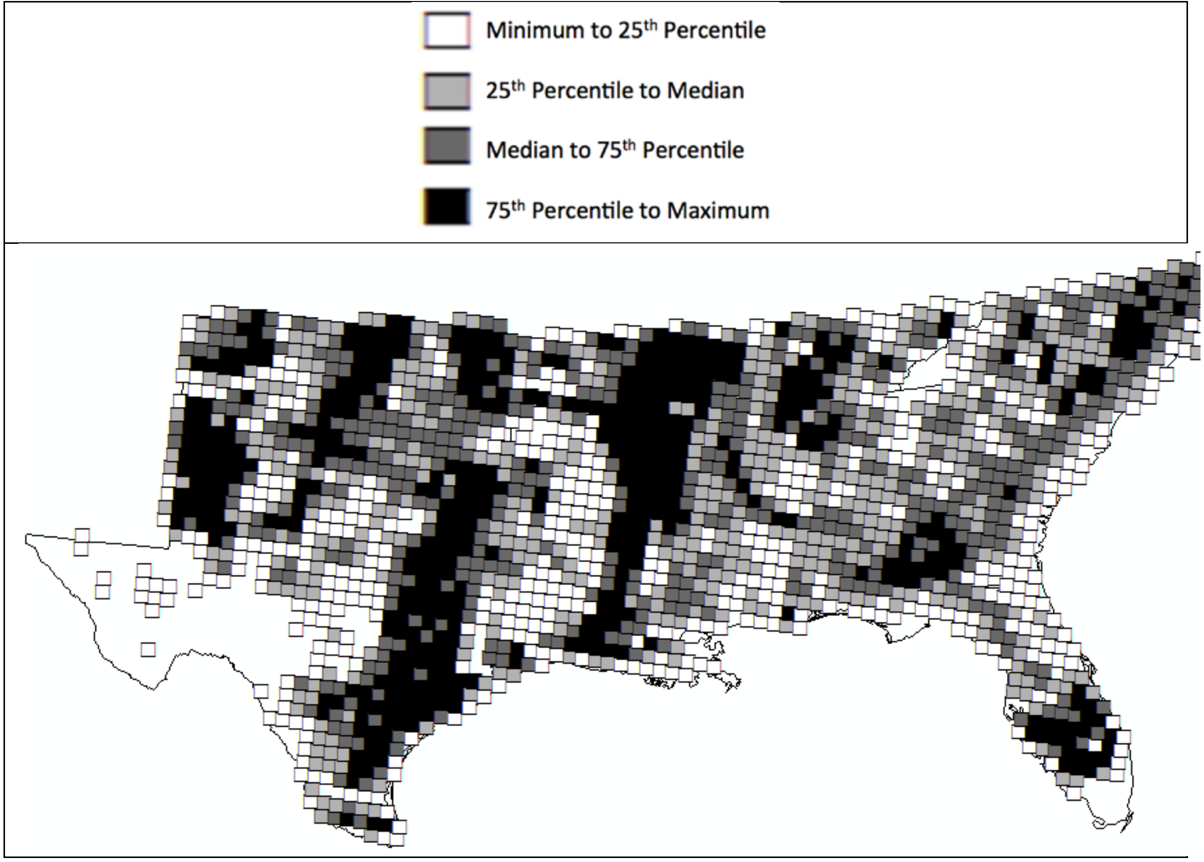
2051

2052

Table 2-10 Crop Yield Statistics (dry Mg/hectare)

	25th Percentile	Median	75th Percentile	Maximum
Mean (1978-2012)	16.1	17.0	17.9	22.7
2008	16.9	17.9	19.2	22.9
2009	15.9	17.2	18.5	23.8
2010	15.7	16.8	18.3	22.4
2011	15.2	17.3	18.8	22.8
2012	12.7	16.0	17.7	24.8
2048	14.4	16.2	17.3	26.3
2049	14.1	16.2	17.7	26.8
2050	13.8	16.4	17.4	25.3
2051	14.4	16.3	17.3	24.9
2052	13.6	16.3	17.1	25.5
Mean (2048-2052)	14.0	16.3	17.2	25.7

Figure 2-3 Available Cropland Acres (Lower quartile: 16503 acres, median: 41928 acres, upper quartile: 79202 acres, maximum: 217416 acres)



Balance on Harvested Biomass in Storage (Centralized Case)

For the centralized case, biomass can be processed at various candidate refinery locations within the region of study, some of which are in the vicinity of oil pipeline terminals. In the case study presented here, all 1908 potential biomass production sites also serve as candidate biorefineries. The material balance on harvested biomass held in storage for the centralized case is described in Equation 2-8 and Equation 2-9 (for harvest locations that do have processing capacity and harvest locations that do not have process capacity respectively) and is as follows: the amount of harvested switchgrass held in storage at location *i* in time period t equals the amount of biomass already in storage (less dry matter loss), plus biomass newly harvested in the previous time period. Harvested biomass is transported from harvest locations that do not have biomass processing facilities to harvest locations that do have processing capacity.

Equation 2-8

$$\mathrm{S}_{\mathrm{ik_2t}} = \mathrm{S}_{\mathrm{ik_2t-1}} \times \left(1 - \mathrm{L}_{\mathrm{k_2}}\right) + \mathrm{B}_{\mathrm{ip_2t-1}} \times \rho_{\mathrm{ik_2p_2t}} - \sum_{\mathrm{p\in p_{9\ldots12}}} \mathrm{B}_{\mathrm{ipt}} + \sum_{\mathrm{i'}} \mathrm{M}_{\mathrm{i'ik_2t-1}} \ \forall \mathrm{i}, \mathrm{t}$$

Equation 2-9

$$\mathrm{S}_{\mathrm{ik_2t}} = \mathrm{S}_{\mathrm{ik_2t-1}} \times \left(1 - \mathrm{L}_{\mathrm{k_2}}\right) + \mathrm{B}_{\mathrm{ip_2t-1}} \times \rho_{\mathrm{ik_2p_2t}} - \sum_{\mathrm{i'}} \mathrm{M}_{\mathrm{ii'k_2t}} \ \forall \mathrm{i}, \mathrm{t}$$

Balance on Oil and Byproduct Production (Mobile Case)

Unlike the centralized case in which biomass is processed only at selected refineries, recall that in the case of mobile processing, small modular units process biomass at the harvest location**,** and a material transfer task transports the crude bio-oil. If the biomass harvest site is located in the vicinity of a pipeline accessible oil terminal, the pyrolysis oil is transported directly via pipeline to a large centralized processing facility for further processing; otherwise it is first transported by truck to a pipeline accessible oil terminal. Conveniently, the final processing step can be conducted within existing petroleum industry infrastructure. The material balance for bio-oil in the mobile case is as follows: the total amount of pyrolysis oil at location *i* as observed in time period *t* equals the quantity of oil that was available in the previous time period, plus oil produced from biomass recently processed in the previous time period, plus net oil shipments. The material balances for oil produced at pipeline accessible and non pipeline accessible harvest sites are represented by Equation 2-10 and Equation 2-11 respectively.

Equation 2-10

$$\mathrm{S}_{\mathrm{ik_3t}} = \mathrm{S}_{\mathrm{ik_3t-1}} + \sum_{\mathrm{P\in p_{3\ldots6}}} \mathrm{B}_{\mathrm{ipt-1}} \times \rho_{\mathrm{ipk_3t}} + \sum_{\mathrm{i'}\in \boldsymbol{R}} \mathrm{M}_{\mathrm{i'ik_3t}} - \sum_{\boldsymbol{f}} \mathrm{M}_{\mathrm{ifk_3t}} \ \forall \mathrm{i} \in \boldsymbol{L}, \mathrm{t}$$

Equation 2-11

$$\mathrm{S}_{\mathrm{ik_3t}} = \mathrm{S}_{\mathrm{ik_3t-1}} + \sum_{\mathrm{P\in p_{3\ldots6}}} \mathrm{B}_{\mathrm{ipt-1}} \times \rho_{\mathrm{ipk_3t}} - \sum_{\mathrm{i'}\in \boldsymbol{L}} \mathrm{M}_{\mathrm{ii'k_3t}}\ \forall \mathrm{i}\ \in \boldsymbol{R}, \mathrm{t}$$

For both the mobile and centralized case, it is assumed that fast pyrolysis byproducts are consumed locally. For the mobile case, the balance for pyrolysis byproducts as follows.

Equation 2-12

$$\mathrm{S}_{\mathrm{i}\boldsymbol{k}_{\boldsymbol{4}\ldots5}\mathrm{t}} = \mathrm{S}_{\mathrm{i}\boldsymbol{k}_{\boldsymbol{4}\ldots5}\mathrm{t-1}} + \sum_{\mathrm{P\in p_{3\ldots6}}} \mathrm{B}_{\mathrm{ipt-1}} \times \rho_{\mathrm{ip}\boldsymbol{k}_{\boldsymbol{4}\ldots5}\mathrm{t}}\ \ \forall \mathrm{i}, \mathrm{t}$$

The biomass processing tasks in the mobile case are limited by the availability of mobile units at a particular harvest location. An overall constraint on biomass processing is represented in Equation 2-13. The parameter values in Table 2-7 identify the monthly capacities for processing tasks. Notice that the processing capacities for setup tasks are smaller than that of processing tasks because capacity is reduced to allow for mobile unit setup time.

Equation 2-13

$$\mathrm{B}_{\mathrm{ipt}} \leq \mathrm{N}_{\mathrm{ipt}} \times \mathrm{Max}_{\mathrm{p}} \forall \mathrm{i}, \mathrm{p}, \mathrm{t}$$

Equation 2-14**,** Equation 2-15**,**

Equation 2-16 and Equation 2-17 apply the general balance for discrete variables introduced in Equation 2-2 explicitly, consistent with the model details provided in Table 2-8.

Equation 2-14

$$\mathrm{N}_{\mathrm{i}\overline{\mathrm{k_6}}\mathrm{t}} = \mathrm{N}_{\mathrm{i}\overline{\mathrm{k_6}}\mathrm{t-1}} + \sum_{\mathrm{i'}} \mathrm{N}_{\mathrm{i'ik_6\,t-1}} + \mathrm{N}_{\mathrm{ip_7\,t}} - \mathrm{N}_{\mathrm{ip_3\,t}}\ \forall \mathrm{i}, \mathrm{t}$$

Equation 2-15

$$\mathrm{N}_{\mathrm{i}\overline{\mathrm{k_7}}\mathrm{t}} = \mathrm{N}_{\mathrm{i}\overline{\mathrm{k_7}}\mathrm{t-1}} + \sum_{\mathrm{i'}} \mathrm{N}_{\mathrm{i'ik_7\,t-1}} + \mathrm{N}_{\mathrm{ip_8\,t}} - \mathrm{N}_{\mathrm{ip_4\,t}}\ \forall \mathrm{i}, \mathrm{t}$$

Equation 2-16

$$\mathrm{N}_{\mathrm{i}\overline{\overline{k_6}}\mathrm{t}} = \mathrm{N}_{\mathrm{i}\overline{\overline{k_6}}\mathrm{t}-1} + \mathrm{N}_{\mathrm{ip}_5\,\mathrm{t}-1} - \mathrm{N}_{\mathrm{ip}_5\,\mathrm{t}} - \mathrm{N}_{\mathrm{ip}_7\,\mathrm{t}} - \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{ii}'_{k_6}\,\mathrm{t}} \;\; \forall \mathrm{i}, \mathrm{t}$$

Equation 2-17

$$\mathrm{N}_{\mathrm{i}\overline{\overline{7}}\mathrm{t}} = \mathrm{N}_{\mathrm{i}\overline{\overline{k_7}}\mathrm{t}-1} + \mathrm{N}_{\mathrm{ip}_6\,\mathrm{t}-1} - \mathrm{N}_{\mathrm{ip}_6\,\mathrm{t}} - \mathrm{N}_{\mathrm{ip}_8\,\mathrm{t}} - \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{ii}'_{k_7}\,\mathrm{t}} \;\; \forall \mathrm{i}, \mathrm{t}$$

Equation 2-18

$$\mathrm{N}_{\mathrm{i}\overline{\overline{k_{6\ldots7}}}\mathrm{t}} \leq Max_{\overline{\overline{k_{6\ldots7}}}} = 0$$

Equation 2-19

$$\mathrm{N}_{\mathrm{ikt}} \geq 0$$

According to Equation 2-14 and Equation 2-15, the number of mobile units before setup equals the number of units before setup in the previous time period, plus units arriving from other harvest sites, plus units that begin a waiting task, less any units that begin setup. According to **Equation 2-16** and Equation 2-17, the number of mobile units after setup equals the number of units after setup in the previous time period plus the number of units that began a processing or setup task in the previous time period, less the number of units that begin a waiting task, a processing task, or begin transport to another location. Notice that according to Equation 2-18, capacities on mobile unit resources in after setup states are zero. Thus, once mobile units complete setup at a particular location, the mobile units must immediately begin a processing or wait task, or must being travel to another location. Mobile units that have recently completed a processing or waiting task can either immediately begin another processing or waiting task or begin travel to another harvest location. Additionally, mobile units cannot commence a waiting or processing task without first completing a setup task. If a mobile unit does choose to begin a waiting task after processing or setup, it must complete another setup task in order to process again. For the purpose of Equation 2-13, processing tasks have full processing capacity, setup tasks have partial setup capacity, and waiting tasks have no processing capacity (further details are included in Table 2-7).

Sufficient mobile processing equipment must be purchased at the beginning of the planning horizon to satisfy processing needs. The mobile processing unit equipment purchase decision is modeled in Equation 2-20. In the first time period of the planning horizon, the number of mobile units located at a particular location, plus the number of units in transit, plus the number of units that begin any tasks must equal the number of units purchased for the network. The balances on processing units described previously guarantee that additional mobile units cannot be added to the network during the planning horizon.

Equation 2-20

$$\sum_{i} N_{ikt_0} + \sum_{i} \sum_{i'} N_{ii'k\,t_0} + \sum_{i} \sum_{p \in \overline{P_k}} N_{ipt_0} = N_k^T \; \forall \; K \in k_{6\ldots7}$$

Balance on Oil at Terminal (Centralized Case)

Once again, the material balances from Equation one can be applied, this time to account for pyrolysis oil in the vicinity of pipeline terminals. In this centralized case, the amount of oil at pipeline terminals equals the amount that was available in previous time units, plus any pyrolysis oil produced by the execution of processing tasks, plus net transport of pyrolysis oil. For selected biorefinery locations with pipelines access, bio-oil is received from processing locations that are not pipeline accessible. Pipeline accessible biorefinery locations also ship pyrolysis oil via pipeline to a final location at which it can be upgraded for use in transportation fuels. The material balance for crude bio-oil at pipeline accessible and non pipeline accessible biorefinery locations is represented in

Equations Equation 2-21 and Equation 2-22 respectively. Pyrolysis byproduct production is expressed in Equation 2-23.

Equation 2-21

$$S_{ik_3t} = S_{ik_3t-1} + \sum_{P\epsilon p_{9 \ldots} p_{12}} B_{i\boldsymbol{p}t-1} \times \rho_{i\boldsymbol{p}k_3t} + \sum\nolimits_{i'\epsilon \boldsymbol{R}} M_{i'ik_3t} - \sum\nolimits_{f} M_{ifk_3t} \;\; \forall i \in \boldsymbol{L}, t$$

Equation 2-22

$$S_{ik_3t} = S_{ik_3t-1} + \sum_{P\epsilon p_{9 \ldots} p_{12}} B_{i\boldsymbol{p}t-1} \times \rho_{i\boldsymbol{p}k_3t} - \sum_{i'\in \boldsymbol{L}} M_{ii'k_3t} \;\; \forall i \in \boldsymbol{R}, t$$

Equation 2-23

$$S_{i\boldsymbol{k_{4 \ldots 5}}t} = S_{i\boldsymbol{k_{4 \ldots 5}}t-1} + \sum_{P\in p_{9 \ldots 12}} B_{ipt-1} \times \rho_{ip\boldsymbol{k_{4 \ldots 5}}t} \;\; \forall i, t$$

The processing capacity constraint for the fixed processing case is outlined in Equation 2-24. Unlike the mobile case, fixed capacity processing involves permanent refinery capacity. The quantity of biomass that can be processed in any particular time period must not exceed the maximum quantity of biomass corresponding to the choice of capacity at refinery locations. The case study presented here includes four capacity options. Also, note that most one refinery can be selected at each location. This is represented in Equation 2-25.

Equation 2-24

$$B_{ip_{9 \ldots 12}t} \leq Max_{p_{9 \ldots 12}} \times W_{ip_{9 \ldots 12}} \; \forall\, i, t$$

Equation 2-25

$$\sum\nolimits_{\boldsymbol{P}\in p_{9 \ldots 12}} W_{ip} \; \leq 1 \forall\, i$$

Balance on Oil produced at Final Refining Location

As mentioned previously, in order for pyrolysis oil to be upgraded to a transportation grade fuel, it must be transported to a suitable refinery for final processing, which can take place within existing petroleum industry infrastructure. This is represented in Equation 2-26.

Equation 2-26

$$\mathrm{S}_{\mathrm{fk}_3\mathrm{t}} = \mathrm{S}_{\mathrm{fk}_3\mathrm{t}-1} + \sum_{\boldsymbol{i}\in\boldsymbol{L}} \mathrm{M}_{\boldsymbol{i}\mathrm{fk}_3\mathrm{t}} \ \forall \mathrm{f}, \mathrm{t}$$

Objective Function

The optimization model presented here employs an economic objective function. The objective functions for the mobile processing and centralized processing case are shown in Equation 2-27 and Equation 2-28.

Maximize

Equation 2-27

$$\mathrm{NPV} = \mathrm{S}_{\mathrm{fk}_3\mathrm{t}_{14}} \times \mathrm{VE}_{\mathrm{k}_3} + \sum_{\mathrm{t}} \sum_{\mathrm{i}} \sum_{\mathrm{P}\in\mathrm{p}_{3\ldots6}} \mathrm{V}_{\mathrm{ip}} \times \mathrm{B}_{\mathrm{ipt}} - \sum_{\mathrm{t}} \sum_{\mathrm{i}} \big(\mathrm{B}_{\mathrm{ip}_1\mathrm{t}} \times \mathrm{CV}_{\mathrm{p}_1} + \mathrm{B}_{\mathrm{ip}_2\mathrm{t}} \times \mathrm{CV}_{\mathrm{p}_2}\big) \times \beta_{\mathrm{i}} - \sum_{\mathrm{t}} \sum_{\mathrm{i}} \sum_{\mathrm{i}'} \mathrm{M}_{\mathrm{ii}'\mathrm{k}\,\mathrm{t}} \times \mathrm{CV}_{\mathrm{ii}'\mathrm{k}_3} - \sum_{\mathrm{t}} \sum_{\mathrm{K}\in\mathrm{k}_{6\ldots7}} \sum_{\mathrm{i}} \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{ii}'\mathrm{k}\,\mathrm{t}} \times \mathrm{CV}_{\mathrm{ii}'\mathrm{k}} - \sum_{\mathrm{K}\in\mathrm{k}_{6\ldots7}} \mathrm{N}^{\mathrm{T}}{}_{\mathrm{k}} \times \mathrm{CF}_{\mathrm{k}}$$

Maximize

Equation 2-28

$$\mathrm{NPV} = \mathrm{S}_{\mathrm{fk}_3\mathrm{t}_{14}} \times \mathrm{VE}_{\mathrm{k}_3} + \sum_{\mathrm{t}} \sum_{\mathrm{i}} \sum_{\mathrm{p}\in\mathrm{p}_{9-12}} \mathrm{V}_{\mathrm{ip}} \times \mathrm{B}_{\mathrm{ipt}} - \sum_{\mathrm{t}} \sum_{\mathrm{i}} \big(\mathrm{B}_{\mathrm{ip}_1\mathrm{t}} \times \mathrm{CV}_{\mathrm{p}_1} + \mathrm{B}_{\mathrm{p}_2\mathrm{t}} \times \mathrm{CV}_{\mathrm{p}_2}\big) \times \beta_{\mathrm{i}} - \sum_{\mathrm{t}} \sum_{\mathrm{K}\in\mathrm{k}_{2\ldots3}} \sum_{\mathrm{i}} \sum_{\mathrm{i}'} \mathrm{M}_{\mathrm{ii}'\mathrm{k}\,\mathrm{t}} \times \mathrm{CV}_{\mathrm{ii}'\mathrm{k}} - \sum_{\mathrm{i}} \sum_{\mathrm{P}\in\mathrm{p}_{9\ldots12}} \mathrm{W}_{\mathrm{ip}} \times \mathrm{CF}_{\mathrm{p}}$$

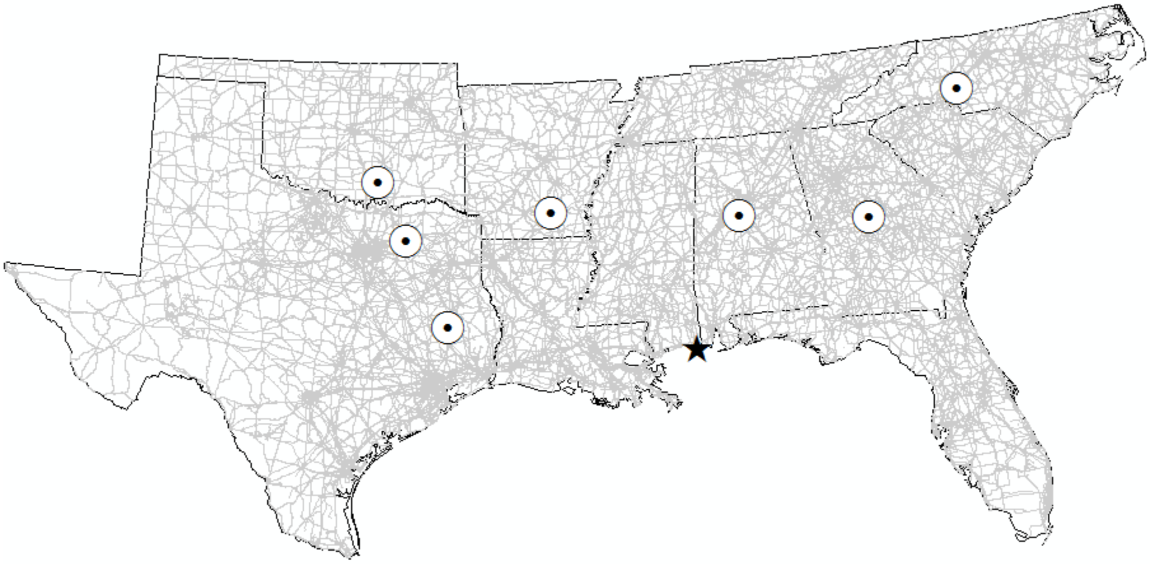
The first term of the objective function for both the mobilized and fixed processing case represent the economic value of crude bio oil that has been delivered to refinery for final processing. The second term represents the economic value of char and gas fast pyrolysis byproducts that are assumed to be used locally less variable processing costs; this is described in Equation 2-29.

Equation 2-29

$$\mathrm{V_{ip}} = \mathrm{VE_{k_4}} \times \mathrm{YE_{k_4}} \times \mathrm{YP_{k_4}} + \mathrm{VE_{k_5}} \times \mathrm{YE_{k_5}} \times \mathrm{YP_{k_5}} - \mathrm{CV_p} \forall \mathrm{P} \in \mathrm{p_{3\ldots6}} \cup \mathrm{p_{9\ldots12}}$$

The third term of the objective function represent planting and harvesting costs, while the fourth term represents material transportation costs. In order to calculate transportation costs among potential harvest locations, between potential harvest locations and oil pipeline terminal locations, and between oil pipeline terminal and the final large refinery location for final fuel upgrade, it was necessary to calculate several transportation distance matrices.   To accomplish this, a Multi Modal Transportation Network dataset (MMNET) was obtained through personal communication with a collaborator in order to calculate the least cost miles between desired locations in the 32 km network used in this study. The Multimodal Network Transportation dataset and pipeline terminal locations and additional candidate biorefinery locations are pictured in Figure 2-4.

Figure 2-4 Candidate Biorefinery Locations, Pipeline Accessible Terminals, and Final Refinery and multimodal transportation network



⊙ Pipeliene Acessible Terminal	★ Final Processing Location

In order to compute CF_{k} for the various required capacities, pyrolysis system equipment costs from Badger 2011 et al are adjusted using a 0.6 scale factor as shown in Equation 2-30.

Equation 2-30

$$\text{Cost} = \text{BaseCost}\left(\frac{\text{New Capacity}}{\text{Base Capacity}}\right)^{.6}$$

Additionally, $\mathrm{CF}_{\mathrm{i'i}}$ is computed by using matrix $\mathrm{D}_{\mathrm{i'i}}$ (calculated using MMNET and OD cost matrix module in Arcmap) along with mobile container variable costs reported in Polagye, Hodgson et al. 2007, which are also scaled according to Equation 2-30.

Since the mobile processing units move between potential biomass harvest locations, and not just between potential biomass locations and large centralized processing facilities, there are many possible movement decisions, and subsequently many integer variables. Additionally, a monthly time step is required in order to properly model planting, harvesting, and the seasonality of biomass availability; this further increases problem size. The full models contains on the order of four hundred thousand equations, six hundred thousand continuous variables, and three hundred sixty thousand discrete variables for each year the model is run. Thus, each of the potential harvest locations is assigned to one of seven oil pipeline terminal locations (pictured in Figure 2-4) by geographic proximity. Separate solutions are obtained for each region and summed. In order to confirm that geographic division does not distort solutions significantly, investigations were conducted in which the net present value of the optimal solution in a particular region was compared the sum of the net present value of the same region divided into two sub regions; the two values differed by less than a third of a percent. These investigations provide evidence for the thesis that geographic subdivision seems not to affect greatly the solution, since there is inherent structure created by natural barriers, such as rivers and mountains, and pipeline infrastructure. Note that the fixed processing model is quite large also since there are many possible transportation links as in the mobile case, and many integer variables since each of the 1908 potential biomass production sites is also a candidate biorefinery.

Results

The biorefinery optimization models described in this chapter were solved using GAMS/Cplex. Case studies for both current yields and future yields (2048-2052) are presented here. For the current yield cases, designs are obtained by solving optimization models using the switchgrass projections based on climate model output data. For the future yield cases, designs are obtained by solving the optimization models using switchgrass projections based on climate modeling conducted by collaborators using the WRF model. For the current yield case, both mobile and fixed processing models are solved for cases in which one, two, ten and twenty percent of available cropland can be planted. These results are summarized in Table 2-11.

Table 2-11 Average Yield Design (1979-2012) by Fraction of Available Cropland that can be planted

	1%		2%		5%		10%		20%	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	8.63E+05	8.85E+05	1.87E+06	1.80E+06	4.78E+06	4.81E+06	9.50E+06	9.75E+06	1.88E+07	2.00E+07
Tons of Biomass Processed	6.28E+06	6.67E+06	1.35E+07	1.36E+07	3.44E+07	3.57E+07	6.81E+07	7.18E+07	1.35E+08	1.45E+08
Planting and Harvesting Costs	2.78E+08	2.85E+08	6.03E+08	5.79E+08	1.54E+09	1.55E+09	3.06E+09	3.14E+09	6.06E+09	6.43E+09
Variable Processing Costs	5.41E+07	8.97E+07	1.16E+08	1.79E+08	2.96E+08	4.84E+08	5.86E+08	9.62E+08	1.16E+09	1.82E+09
Processing Capacity	8.41E+06	2.45E+07	1.65E+07	3.68E+07	3.93E+07	6.37E+07	7.55E+07	1.23E+08	1.43E+08	2.58E+08
Capacity Used	75%	27%	82%	37%	87%	56%	90%	59%	94%	56%
Fixed Processing Costs	3.78E+08	1.49E+08	7.36E+08	2.18E+08	1.74E+09	3.96E+08	3.33E+09	7.51E+08	6.31E+09	1.47E+09
Mobile Unit Setup Cost	9.97E+05	--	1.50E+06	--	2.18E+06	--	2.22E+06	--	2.35E+06	--
Mobile Unit Transportation Cost	1.94E+05	--	2.80E+05	--	3.53E+05	--	2.26E+05	--	4.88E+04	--
Cost Oil Transport Truck	9.19E+07	7.96E+07	1.99E+08	1.67E+08	5.09E+08	4.44E+08	1.01E+09	9.69E+08	2.00E+09	2.04E+09
Cost Oil Transport Pipeline	5.34E+07	5.76E+07	1.15E+08	1.15E+08	2.93E+08	3.04E+08	5.79E+08	6.11E+08	1.15E+09	1.24E+09
Cost Harvested Biomass Transport Truck	--	2.68E+08	--	5.00E+08	--	9.61E+08	--	1.33E+09	--	1.97E+09
Oil and Byproduct Value	1.25E+09	1.21E+09	2.69E+09	2.46E+09	6.86E+09	6.47E+09	1.36E+10	1.29E+10	2.68E+10	2.61E+10
Transportation Cost ($/ton)	23.33	60.76	23.44	57.61	23.40	47.85	23.38	40.54	23.40	36.11
Processing Cost ($/ton)	68.79	35.80	63.24	29.25	59.22	24.64	57.54	23.87	55.45	22.63
NPV	3.91E+08	4.01E+08	9.21E+08	9.53E+08	2.48E+09	2.99E+09	5.04E+09	6.57E+09	1.01E+10	1.40E+10

For the case in which 10% of available cropland can be planted, the transportation connections for mobile processing units are pictured in Figure 2-5. The harvested biomass transportation connections for the corresponding centralized model are pictured in Figure 2-6. The transportation connections for the movement of crude bio-oil to pipeline accessible locations and subsequently, the final processing facility for the mobile case are pictured in Figure 2-7. Finally, the movement of crude bio oil from centralized biorefinery to pipeline accessible locations and from pipeline accessible locations to final processing location for the centralized case is pictured in Figure 2-8.

Figure 2-5 Mobile Transportation Connections (Mobile Processing Case, 1978-2012 average yields, 10% Maximum Planting Fraction)

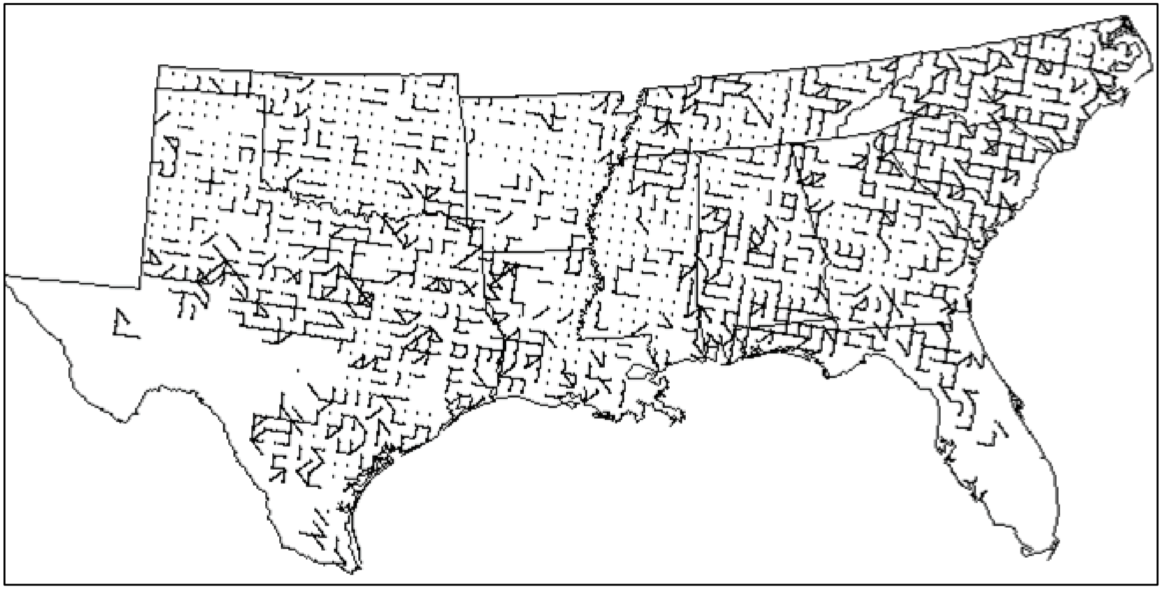


Figure 2-6 Harvested Biomass Transportation Connections (Fixed Processing Case, 1978-2012 average yields, 10% Maximum Planting Fraction)

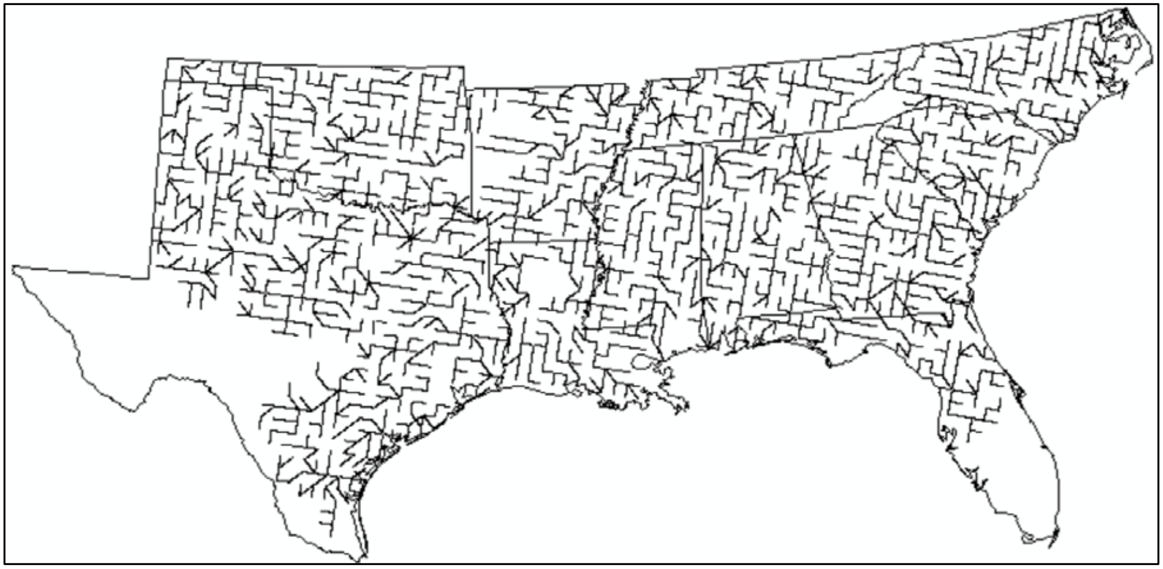


Figure 2-7 Crude Bio-Oil Transportation Connections (Mobile Processing Design Case, 1978-2012 Average yields, 10% Maximum Planting Fraction)

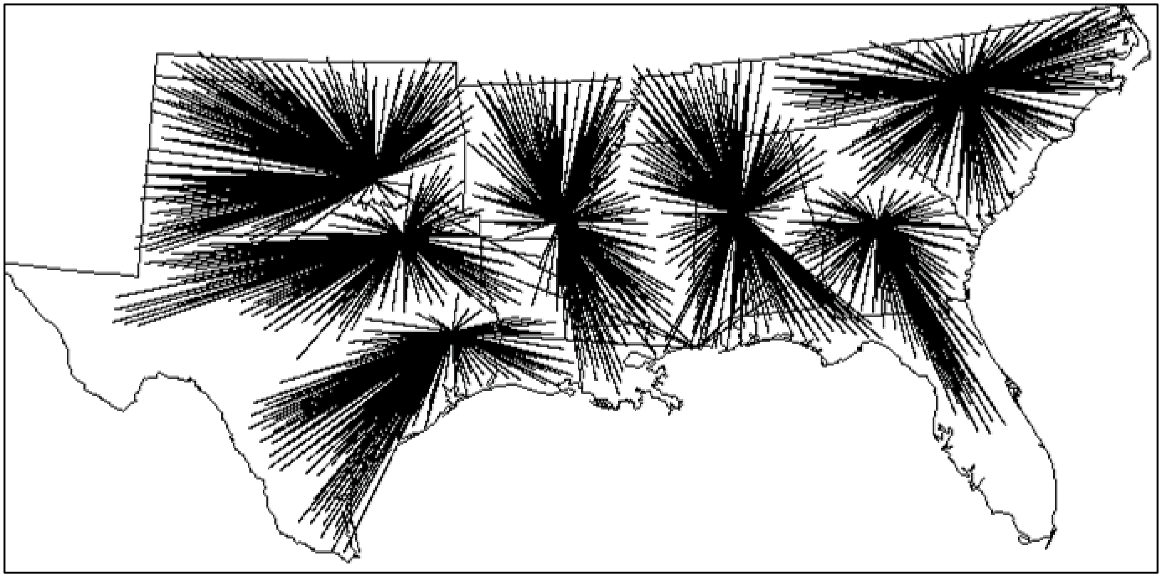
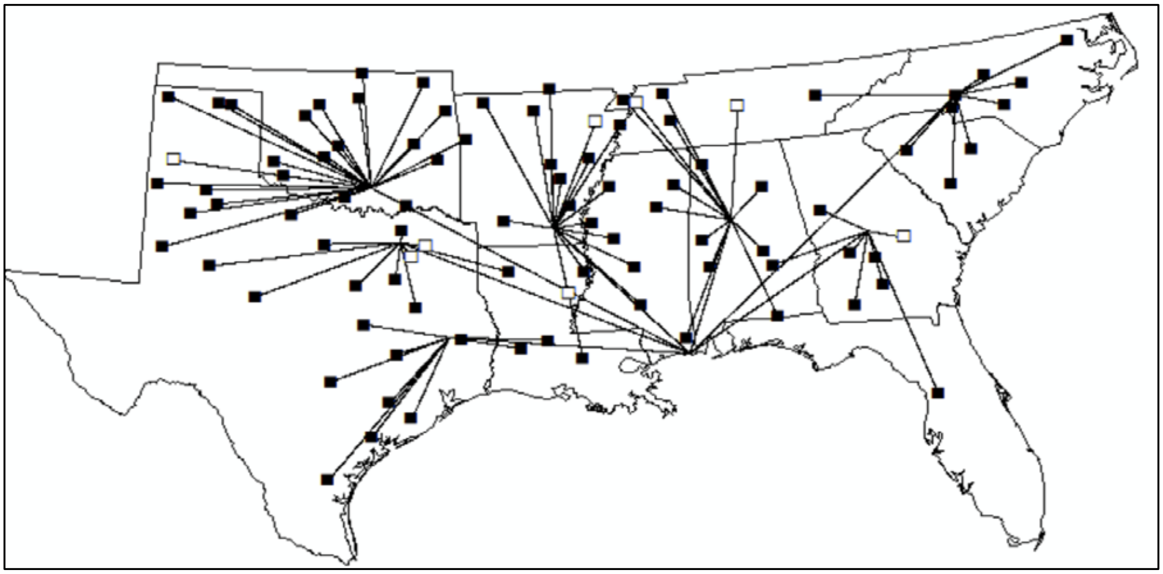


Figure 2-8 Crude Bio-Oil Transportation Connections (Centralized Processing Design Case) and refinery capacity decisions (1978-2012 Average yields, 10% Maximum Planting Fraction)



For the future yield case, the mobile and centralized processing models are solved for cases in which ten percent of available cropland can be planted. Individual designs for 2048-2052 are included in this chapter. In order to compare the future results to a five-year period representing current climate conditions, individual designs for the years 2008-2012 are also included. Results for the 2008-2012 and 2048-2052 case studies are summarized in Table 2-12 and Table 2-13 respectively.

Table 2-12 2008-2012 with maximum planting fraction of 10%

	2008		2009		2010		2011		2012	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	9.35E+06	9.66E+06	9.44E+06	9.72E+06	9.81E+06	1.02E+07	9.53E+06	9.72E+06	8.98E+06	9.41E+06
Tons of Biomass Processed	7.10E+07	7.52E+07	6.79E+07	7.17E+07	7.08E+07	7.56E+07	7.04E+07	7.42E+07	6.13E+07	6.57E+07
Planting and Harvesting Costs	3.01E+09	3.11E+09	3.04E+09	3.13E+09	3.16E+09	3.27E+09	3.07E+09	3.13E+09	2.89E+09	3.03E+09
Variable Processing Costs	6.11E+08	9.95E+08	5.85E+08	9.62E+08	6.10E+08	9.58E+08	6.06E+08	9.77E+08	5.28E+08	8.40E+08
Fixed Processing Costs	3.44E+09	8.10E+08	3.31E+09	7.33E+08	3.46E+09	8.97E+08	3.43E+09	7.48E+08	2.98E+09	7.93E+08
Mobile Unit Setup Cost	2.12E+06	--	2.07E+06	--	2.26E+06	--	2.30E+06	--	1.90E+06	--
Mobile Unit Transportation Cost	2.02E+05	--	2.06E+05	--	2.27E+05	--	2.30E+05	--	1.91E+05	--
Cost Oil Transport Truck	1.04E+09	1.01E+09	1.01E+09	9.73E+08	1.10E+09	1.06E+09	1.05E+09	9.97E+08	9.06E+08	8.75E+08
Cost Oil Transport Pipeline	6.03E+08	6.38E+08	5.77E+08	6.08E+08	6.08E+08	6.47E+08	5.97E+08	6.29E+08	5.19E+08	5.54E+08
Cost Harvested Biomass Transport Truck	--	1.36E+09	--	1.32E+09	--	1.44E+09	--	1.44E+09	--	1.23E+09
Oil and Byproduct Value	1.41E+10	1.35E+10	1.35E+10	1.29E+10	1.41E+10	1.35E+10	1.40E+10	1.33E+10	1.23E+10	1.18E+10
NPV	5.42E+09	7.03E+09	4.98E+09	6.60E+09	5.18E+09	6.78E+09	5.27E+09	6.82E+09	4.44E+09	5.77E+09

Table 2-13 2048-2052 with maximum planting fraction of 10%

	2048		2049		2050		2051		2052	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	8.17E+06	8.60E+06	8.26E+06	8.73E+06	8.32E+06	8.66E+06	8.14E+06	8.91E+06	8.14E+06	8.48E+06
Tons of Biomass Processed	5.78E+07	6.20E+07	5.78E+07	6.19E+07	5.82E+07	6.18E+07	5.73E+07	6.25E+07	5.77E+07	6.10E+07
Planting and Harvesting Costs	2.63E+09	2.77E+09	2.66E+09	2.81E+09	2.68E+09	2.79E+09	2.62E+09	2.87E+09	2.62E+09	2.73E+09
Variable Processing Costs	4.98E+08	8.20E+08	4.98E+08	8.13E+08	5.01E+08	8.11E+08	4.93E+08	8.31E+08	4.97E+08	8.12E+08
Fixed Processing Costs	2.80E+09	6.50E+08	2.81E+09	7.22E+08	2.83E+09	6.66E+08	2.78E+09	6.79E+08	2.82E+09	6.17E+08
Mobile Unit Setup Cost	1.68E+06	--	1.86E+06	--	1.72E+06	--	1.68E+06	--	1.58E+06	--
Mobile Unit Transportation Cost	1.57E+05	--	1.95E+05	--	1.62E+05	--	1.56E+05	--	1.34E+05	--
Cost Oil Transport Truck	9.24E+08	9.00E+08	9.21E+08	9.13E+08	9.22E+08	8.95E+08	9.11E+08	9.06E+08	9.26E+08	9.00E+08
Cost Oil Transport Pipeline	5.15E+08	5.50E+08	5.14E+08	5.48E+08	5.15E+08	5.46E+08	5.06E+08	5.48E+08	5.15E+08	5.43E+08
Cost Harvested Biomass Transport Truck	--	1.18E+09	--	1.09E+09	--	1.14E+09	--	1.12E+09	--	1.12E+09
Oil and Byproduct Value	1.15E+10	1.11E+10	1.15E+10	1.11E+10	1.15E+10	1.11E+10	1.14E+10	1.12E+10	1.15E+10	1.09E+10
NPV	4.18E+09	5.50E+09	4.14E+09	5.48E+09	4.10E+09	5.52E+09	4.13E+09	5.52E+09	4.17E+09	5.44E+09

Discussion and Conclusions

Comparing the mobile processing design to the fixed capacity design is in essence an investigation of the implications of moving harvested biomass (fixed processing) as opposed to moving the processing capacity (mobile processing design). In general, it is expected that transportation costs for mobile processing will be lower than that of fixed processing, while processing costs for fixed processing will be lower that of mobile processing. This phenomenon is pictured in Figure 2-9 and Figure 2-10. Note that the relative impact of this general principle varies depending on the fraction of available cropland at each location in the network that can be dedicated to energy crop growth.

According to Table 2-11, the transportation costs per ton of biomass processed remains relatively constant with increasing maximum planting fraction for the mobile processing case, while the transportation cost per ton of biomass processed decreases with increasing maximum planting fraction for the fixed capacity case. This phenomenon is illustrated Figure 2-10 in which the Per Unit Transportation costs are pictured. Yet, as maximum planting fraction increases the gap in transportation costs between to the two designs narrows (Figure 2-10), while the gap in processing costs remains relatively constant (Figure 2-9). It is worth mentioning that the gap between centralized processing costs and mobile processing costs could in part be attributed to the fact that mobile processing technology is in its infancy stage.

Figure 2-9 Per Unit Processing Costs

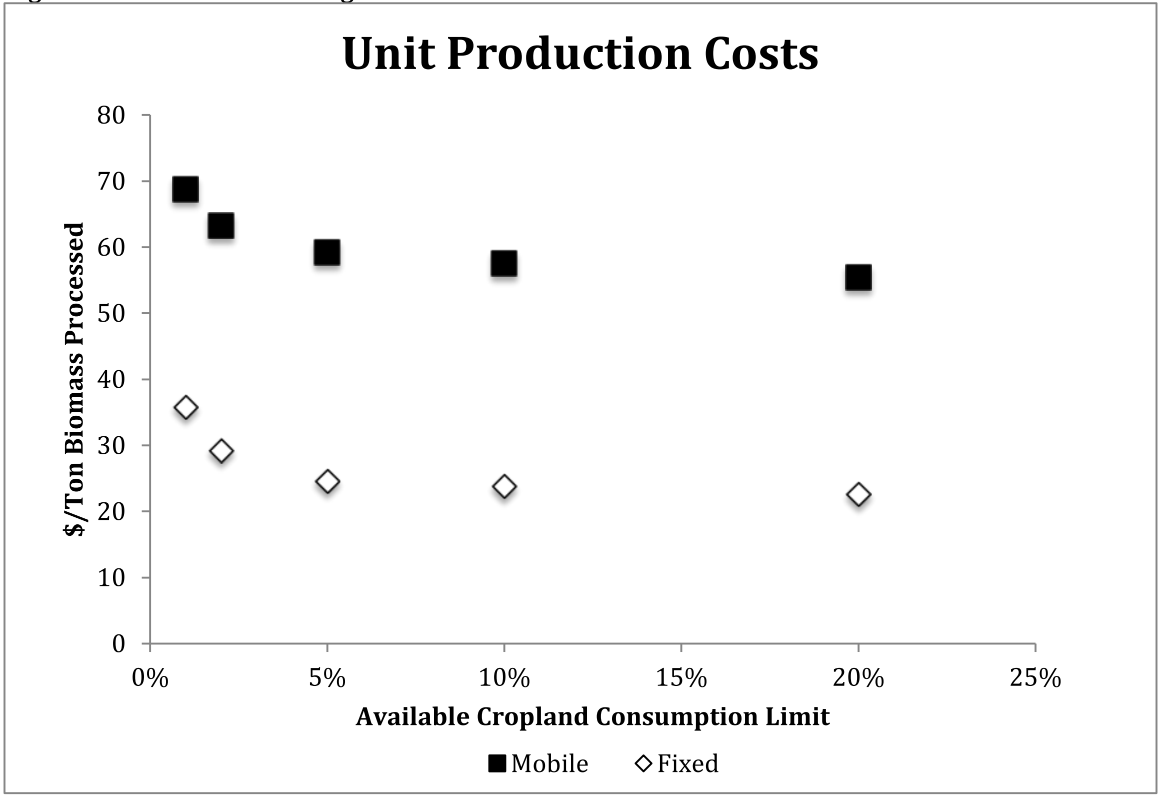
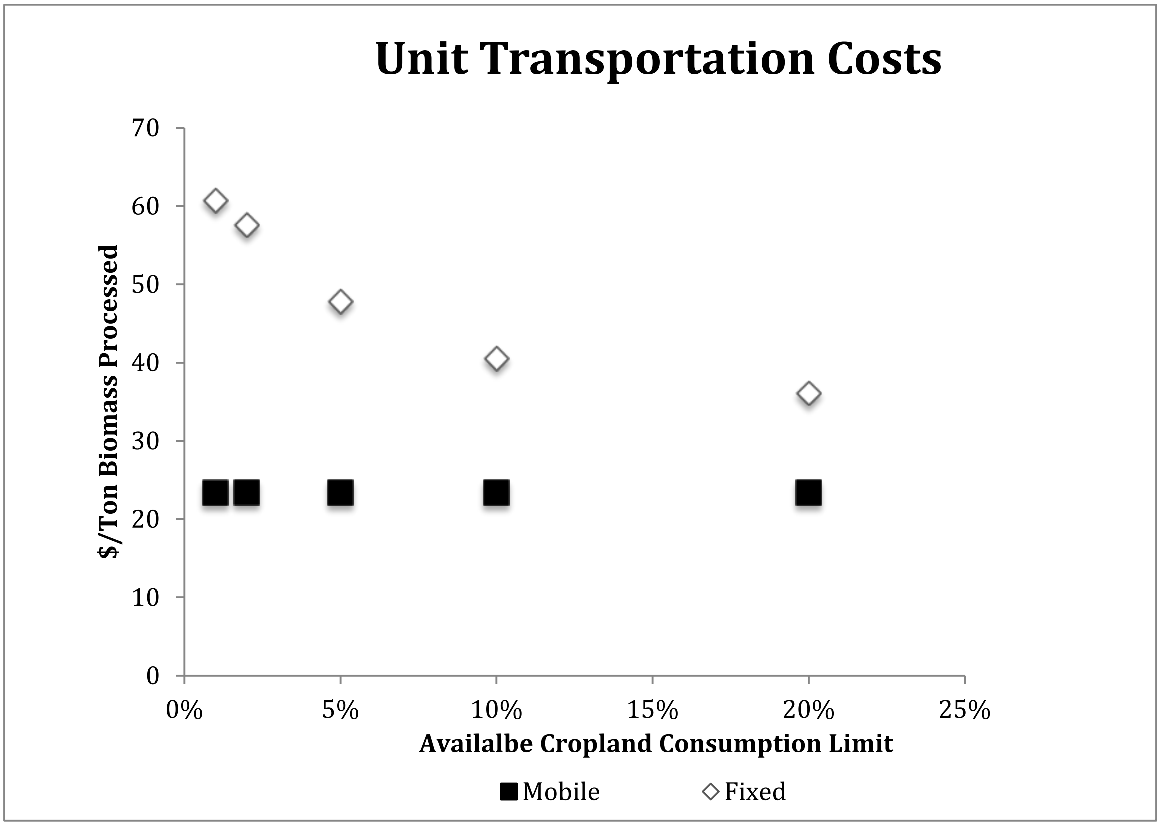


Figure 2-10 Per Unit Transportation Costs



The components of transportation costs in Table 2-11, Figure 2-9, and Figure 2-10 for the mobile processing case include the following:

- The cost of transporting (via truck) crude bio-oil from harvest locations location at which it is processed to pipeline accessible terminals
- The cost of transporting crude bio-oil from the pipeline accessible terminals to the final processing location (via pipeline)
- The cost of transporting mobile units among harvest locations

The corresponding transportation costs for the fixed processing case are as follows:

- The cost of transporting harvested biomass from harvest location to selected processing facilities via truck
- The cost of transporting crude bio-oil from processing facility to pipeline accessible terminals
- The cost of transporting crude bio-oil from pipeline accessible terminals to the final processing location via pipeline

Recall that Figure 2-5, Figure 2-6, Figure 2-7, and Figure 2-8 reflect a scenario in which the optimization models are solved using the average of the projected yields from 1979-2012 at each location in the network with a maximum planting policy of 10% of the available cropland acres at each location. Notice that in Figure 2-5 there are singular dots in addition to connected lines that indicate transportation routes. The singular dots indicate areas at which processing takes place, but mobile units do not move. These dots tend to occur at locations signified by high biomass yield and/or greater supply of cropland acres as indicated in Figure 2-1 and Figure 2-3 respectively. According to Table 2-11, at a 10% of available cropland maximum planting policy, the mobile processing network is operating at greater than 90% capacity, a stark contrast to the 59% capacity at which the fixed processing network operates. Thus, at locations in which singular dots appear in Figure 2-5, there is likely sufficient biomass available for some mobile units to operate at reasonable capacity without moving.

While Figure 2-6 shows the movement of harvested biomass for the fixed processing case, Figure 2-8 shows the movement of crude bio-oil and the selected fixed processing locations at which harvested biomass is converted to pyrolysis oil. While the fixed processing design decisions included four possible processing capacities (1.225-4.9

million tons per year), the model selected only two capacities. Notice that the dark squares in Figure 2-8 represent the locations at which the smallest processing capcity is selected, while the larger squares represent the locations at which the second to smallest capacity is selected. As indicated in the figure, the vast majority of the selected facilities are of the smallest processing capacity, indicating that in general, smaller more distributed facilities are favored, which is likely due to the decreased transportation costs associated with smaller production facilities. The lines in Figure 2-8 represent the movement of pyrolysis oil from the fixed facilities to pipeline accessible terminals, and finally from terminals to the final processing facility via pipeline. This can be compared to Figure 2-7, in which the movement of pyrolysis oil from harvest locations to pipeline accessible terminals, and finally from terminals to the final processing facility via pipeline is pictured for the mobile case.

Table 2-12 and Table 2-13 provide results derived from running the optimization models with yield data for selected five-year periods using current and future climate conditions. For all such scenarios, a maximum planting fraction policy of 10% of available cropland acres is enforced. Figure 2-1, Figure 2-2, and Table 2-10 are particularly useful when examining these results as they illuminate the difference in yield patterns among the years examined that are driving the difference in model results. The future scenario seems to have a smaller lower quartile value and larger maximum value than that of the current climate condition scenario. Additionally, it seems that median yield is greater in the current scenarios than in the future scenarios. The results indicate that lower profit is expected when solving the optimization model using climate model output data from future climate scenarios.

Thus far the performance of mobile and fixed processing supply has been compared for various maximum-planting policies, yield patterns, and climate scenarios. In general, the current climate scenarios seem to perform better than the future climate scenarios in terms of NPV. In addition, while the mobile processing cases provided the benefit of lower transportation costs, even in cases of lower switchgrass planting density, the lower transportation costs did not compensate for the decreased processing costs associated with fixed processing units. Overall, the NPV for mobile processing scenarios was roughly 75-80% of that of the fixed processing scenarios. This is somewhat misleading because while this study has focused on determining biorefinery network solutions for single year conditions, it does not fully exploit all of the potential advantages of mobile processing. In reality some biorefinery design decisions will be fixed at the beginning of the project period. For example, since switchgrass is a perennial crop with a stand life of approximately ten years, planting is one example of a decision that would be fixed at the beginning of the planning horizon. For the case of fixed processing, the location and capacity of processing facilities is also a decision that would be fixed at the beginning of the planning horizon. After these fixed decisions are made, yield patterns are realized and processing and transportation decisions are made; this occurs annually for the life of the project. Notice that for the mobile processing case, planting is fixed for the planning horizon, but processing capacity is not. In essence, the mobile processing system can adjust processing capacity on an annual basis. This is a degree of flexibility inherent in the mobile processing design case that is not exploited in this model. Future chapters will explore the use of a multi period planning problem to quantify the utility of this additional flexibility. Even without considering the multi period planning problem, the gap in NPV between the mobile and fixed processing infrastructure could narrow with increased adoption of mobile processing. Large-scale fast pyrolysis is relatively mature industry compared to mobile fast pyrolysis. Thus, the mobile processing may experience decreased production costs relative to centralized processing as the mobile processing industry matures and the production rate of mobile pyrolysis units increases.

CHAPTER 3 Yield Model Description

There are both environmental and economic benefits of switchgrass as a biofuel crop that include carbon sequestration, soil improvement and the promotion of biodiversity (Keshwani and Cheng 2009, Hartman, Nippert et al, 2011). In fact, the Department of Energy has identified switchgrass as an important crop for biofuel production because of its potential to reduce carbon dioxide emissions, improve soil conditions, and absorb nitrogen from fertilizer and agricultural wastes (Bransby, McLaughlin et al. 1998, Hartman, Nippert et al. 2011). Another advantage of switchgrass is that it has low agricultural input requirements; switchgrass can be cultivated using standard agricultural equipment and can contirbute to erosion control (Keshwani and Cheng 2009, Wright 1994). Additionally, the potential for high yields makes switchgrass a viable candidate for conversion to ethanol through saccharification and fermentation and the production of liquid fuels through thermo chemical conversion through pyrolysis (David and Ragauskas 2010). Since, switchgrass has been identified as an important crop for biofuel production, predicting the expected yield of switchgrass for particular growing seasons is a problem of interest.

There have been many previous efforts geared toward predicting the effect of climate and management variables on expected switchgrass harvests. The studies vary in scope, model complexity, validation efforts, and relative success. Some models are site specific, while others are regional models that are applicable to large geographic areas. Many of the switchgrass modeling studies can be organized into two broad categories; statistical models, and mechanistic models.

The mechanistic crop yield models simulate real biological processes at particular time scales. The statistical models use switchgrass field trials from various sources to demonstrate the contribution of climate and management variables on the overall variance in observed switchgrass yields. Examples of proposed statistical models include general additive models and linear or nonlinear regression based models.

This chapter presents both a statistical and a mechanistic yield model for both upland and lowland switchgrass cultivar varieties. Both the statistical and mechanistic models are trained using switchgrass field trial yield data and weather and soil data sets. Finally, annual yield model projections for the southeastern United States are presented using both current (1978-2012) and future (2048-2052) climatic conditions. The importance of the future projections is that they will help to illuminate effects of climate change on the biomass availability landscape. Specifically, it will be of interest to note whether meeting bioenergy targets will be more difficult in future climate scenarios.

Review of Statistical Crop Models

Schmer, Mitchell, Vogel, Schacht, and Marx (2010a)/(2010b) examine the spatial and temporal variation in observed switchgrass yields at 10 fields in North Dakota, South Dakota, and Nebraska over the span of five years. The study confirms that switchgrass yield modeling can be conducted using field scale observed yields, as within field affects were insignificant. Other important findings are that the majority of temporal variation in observed switchgrass yields stems from weather variability. The study also highlights some important observations about stand age. Specifically, more modest switchgrass yields can be expected in the first two years of stand establishment.

Another statistical approach was conducted by Wang, Lebauer, and Dietze (2010), who study the effects of climate and management on switchgrass yields. In particular, this work focuses on examining how climate and management affect monocultures and switchgrass species yields differently. Interesting findings of this work are that switchgrass yields increase with nitrogen application and increased precipitation for monocultures but not mixtures. Additionally, observed yields were twice as high in monocultures.

Aravindhakshan, Epplin, and Taliaferro (2010) assert that switchgrass is the model energy crop for the United States, while miscanthus is the model energy crop for Europe. This study uses a statistically based approach to demonstrate this by comparing switchgrass and miscanthus yields in the United States. To accomplish this, field trial data from Oklahoma is obtained and a regression model that includes species type, harvest frequency, and interaction effects is presented. In addition to determining which crop (switchgrass or miscanthus) is the most economically viable option in the United

States, the study seeks to also determine preferred harvest frequency. According to findings, a single harvest of switchgrass was most advantageous.

In later studies, Aravindhakshan, Epplin, and Taliaferro (2011) used Oklahoma field trial data to determine the optimal harvest frequency, nitrogen application and perennial grass species that would maximize crop yield. This was accomplished by estimating linear response plateau, linear response stochastic plateau, and quadratic response functions. This study determined switchgrass to be the biofuel crop of choice when compared to bermudagrass, weeping lovegrass, and carostan flaccidgrass.

Some switchgrass modeling studies have attempted to analyze larger geographical areas and pose predictive models. Wullschleger, Davis, Borsuk, Gunderson, & Lynd, 2010 propose a parametric general additive model for switchgrass yields based on 39 field trials. Parameters include growing season precipitation, annual temperature, nitrogen input, and ecotype. This study reports R^2 values of 0.34 for the natural logarithm of biomass yield. Crop yield simulations for the United States are also presented in this work.

Tulbure, Wimberly, Boe, and Owens (2012) also use a general additive model to predict switchgrass yields over a large geographic area. This study predicts upland and lowland switchgrass yields using nonlinear functions. This model is trained using observed yield data from 15 states. Temperature and precipitation input parameters for this study are from the PRISM model, (Parameter-elevation Regressions on Independent Slopes Model), (Prism Climate Group, 2009) while soil parameters (percent soil , clay, and silt) are from NRCS State Soil Geographic Data. Random forest is used to determine variable importance, while a general additive model is used for predictive purposes. For both upland and lowland ecotypes, the random forest model explains 75% of variance. The study claims that nitrogen application and cultivar type are the main drivers of switchgrass yields. Additionally, the relative importance of weather predictors seemed to be cultivar dependent. In particular, for upland ecotypes, temperature was the driving force of variance in observed yields, while precipitation was the most important predictor for lowland ecotypes. When considering ecotypes separately, the model explains 45% and 61% of variation in upland and lowland cultivars respectively.

Jager et al. (2010) obtained field trial data sets that span North America, (although the majority of the data points are from the southeastern United States) and developed a spatially explicit empirical switchgrass model. Soil and weather data for this study are obtained from the PRISM (Prism Climate Group, 2009) and STATSGO (United States Soil Conservation Service., 1992) respectively. Results showed a positive relationship between average temperature and precipitation for both cultivars. The upland cultivar showed a significant positive response to soil moisture index (derived from precipitation and the fraction of sand in local soil), while the lowland cultivar did not. Empirical modeling results are compared to mechanistic models shown in the literature, and the authors opine that empirical models should not replace mechanistic models. Instead, they suggest that empirical models can be applied on a large spatial scale and be used to improve mechanistic models by exposing inconsistencies between mechanistic models and empirical data. Upland cultivar correlation coefficients of 0.62 and 0.58 are reported for training and testing data respectively. For lowland varieties, correlation coefficients are 0.46 and 0.19 respectively. The statistical crop model presented in this thesis is most similar to that of Jager, Baskaran et al. 2010, with the exception that harvest frequency and stand age were not included in the model presented here. Additionally, the model presented in this thesis uses the fraction of available soil available water holding capacity in lieu of the soil moisture index parameter from Jager et al. (2010).

Beer’s Law Mechanistic Models

In addition to a statistical crop model, this chapter will also present a mechanistic model based on Beer’s Law. There have been several previous mechanistic switchgrass yield modeling efforts based on Beer’s Law; many of these models simulate crop development as a function of heat units (derived from temperature data), leaf area index as a function of crop development, fraction of photosynthetically active radiation intercepted as a function of leaf area index, and above ground biomass as a function of intercepted radiation. In many cases, leaf area index and radiation use efficiency can be limited by environmental factors such as temperature or soil moisture stress. Complex mechanistic models can include detailed leaf level carbon and nitrogen cycling. Additionally, some mechanistic models focus on the effects of switchgrass planting on soil and water quality.

A number of Beer’s Law based models make adaptations to mechanistic crop yield models that have been validated for traditional agricultural crops in order to form yield predictions for switchgrass and other bioenergy crops. Numerous studies have used the EPIC (Environmental Policy Integrated Climate) and ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) models in this fashion. Brown, Rosenberg, Hays, Easterling, and Mearns (2000) use EPIC to explore switchgrass production in the Missouri-Iowa-Nebraska-Kansas region for both current and future climate scnearios and compare results to that of winter wheat and corn. In that study, crop growth can be limited by soil moisture, solar radiation, and nutrient deficits.

Findings show that since switchgrass performs better at higher temperatures, switchgrass yield increases are observed in future climate scenarios. For all scenarios, switchgrass was shown to consume more water and reduce soil erosion and surface runoff.

J. R. Kiniry et al. (2005) evaluate the ALMANAC model for switchgrass at sites in the states of Texas, Arkansas, and Alabama. Simulated yields were within two percent of mean observed yields at each location. Correlation between measured and predicted switchgrass yield varied widely from 0 to 0.9 depending on the site location, but three out of four locations showed a correlation coefficient greater than 0.62. Additionally, the model accounted for 47% of the variation in switchgrass yield across all locations. J. R. Kiniry et al. (1996) evaluate ALMANAC at six sites in Texas and report a correlation between measured and predicted yields of 0.79.

Persson, Ortiz, Bransby, Wu, and Hoogenboom (2011) evaluate the ALMANAC model using data from field trials at five locations in the state of Alabama in order to perform yield projections for 13 counties in the Tennessee River Valley region of northern Alabama and Georgia for three eight year periods. Adjustments to parameters for yield loss due to freezing are also incorporated in order to minimize the unrealistically large yield losses originally modeled using ALMANAC default parameters. Model inputs included daily temperature, rainfall, and solar radiation data; these input parameters are obtained from the National Climatic Data Association (NCDC) Cooperative Observer Program (COP) weather station data and a solar radiation generator. This study reports an overall root mean square error of 6.6 Mg/ha with an average yield of 15.5 Mg/ha.

Grassini, Hunt, Mitchell, and Weiss (2009) propose a simplified Beer's Law based model that predicts yield using daily temperature, precipitation, soil radiation, and site-specific soil data sets. Despite the simplifications, this study predicts the date of anthesis, which is not considered in EPIC and ALMANAC. The model was able to predict date of anthesis and above ground biomass at three independent sites within 3 days and 1.5 Mg/h respectively. This study included the use of datasets that span a wide geographic area. The High Plains Regional Climate Center (University of Nebraska-Lincoln) supplied the weather and soil data for this work.

Agriculturally Focused Models using EPIC/ALMANAC

There are several examples of studies that use EPIC and ALMANAC modules in studies that focus on agriculture, and the soil, water, and environmental implications of biofuel production. For example, Powers, Ascough, Nelson, and Larocque (2011) combine EPIC with the APEX model (Agricultural Policy/Environmental eXtender) in order to assess the effects of removing corn stover and producing herbaceous energy crops. The APEX model is a daily time step simulation model that uses weather parameters such as precipitation, solar radiation, and temperature to produce crop yield and water quality estimates. The model is designed to be applicable to a variety of spatial scales. The field simulation routine incorporates modules from the EPIC model.

Landers, Thompson, Kitchen, and Massey (2012) use ALMANAC to calculate break-even costs for switchgrass in the clay pan soil region. The study reports an average projected switchgrass yield of 12.56 Mg/ha and concludes that switchgrass can be competitive with conventional crops in areas characterized by marginal and eroded soils

McLaughlin, Kiniry, Taliaferro, and Ugarte (2006) combine ALMANAC with an econometric model, POLYSYS, to model the variability in water use and production of switchgrass and corn.

Graham, English, and Noon (2000) calculate the farmgate cost of switchgrass at a one square kilometer resolution by integrating Geographic Information Systems (GIS) and land use and transportation models with the EPIC crop growth yield model.

Jain, Khanna, Erickson, and Huang (2010) simulate switchgrass and miscanthus yields using a mechanistic model and data obtained from two years of field trials in Urbana Illinois and perform model validation at a total of six sites in the state of Illinois. Switchgrass parameters calculated during the calibration process include leaf area index, radiation use efficiency, and light extinction coefficient. Growing degree days to maturity and length of growing season are also calculated. Model Inputs include daily weather data at a resolution of a tenth of a degree. These values are generated from 4 km monthly climate data sets. Results indicate over prediction of switchgrass yields by 4%. The yield projections from this study also serve as input to an economic model in order to perform break-even calculations using county-level enterprise budgets. The overall model was run for the United States and results are presented for the Midwestern United States. The study uses EPIC modules for solar radiation (Williams & Sharpley, 1990) and uses a weather generator WGEN(Richardson, 1984) to calculate daily soil radiation values. Temperature and precipitation data is from PRISM (Prism Climate Group, 2009), while the methods of Liu, Williams, Wang, and Yang (2009) are used to calculate daily values. Finally, soil temperature is gathered from the NASA Earth Science Division and Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

Other Agriculturally Focused Mechanistic Models

Khanna, Dhungana, and Clifton-Brown (2008) estimate the cost of producing switchgrass and miscanthus in Illinois by combining MISCAMOD, a biogeophsical crop yield model with both county level land opportunity costs data and detailed switchgrass production machinery estimates. Weather data is collected from 19-186 locations (depending on data product) and interpolated to a 2 km grid by kriging or inverse distance weighting as appropriate. Corson, Rotz, and Skinner (2007) use the farm system model to predict switchgrass production in Pennsylvania using soil radiation, temperature, and precipitation inputs. Seven of the thirteen predicted yields were within thirty three percent of mean observed yields. The study views warm season grasses as preferable due to their increased photosynthetic rate at higher temperatures in addition to favorable water and nitrogen use efficiency properties. This particular study focused on the use of switchgrass for cattle grazing as opposed to a biofuel feedstock.

Gopalakrishnan, Negri, and Salas (2012) model switchgrass and miscanthus using DNDC, a complex nitrogen and carbon cycling model that that considers climate, soil, and crop growth parameters. The model is calibrated at sites in the state of Illinois; calibration efforts include field measurements of nitrous oxide. One unique aspect of this model is that is assumes that crops are to be grown adjacent to agricultural crops in order to absorb nutrient runoff. The model was very successful at predicting switchgrass yields at the field scale, but the authors suggest the need for model validation at larger scales. Several other modeling studies examine soil and water quality factors. Qin, Zhuang, and Chen (2012) use the Terrestrial Ecosystem Model, a global-scale ecosystem model, to simulate carbon and nitrogen fluxes and subsequently net primary productivity for corn, soybean, wheat, switchgrass, and miscanthus. The model was calibrated using soil texture data, monthly climate data from the Climate Research Unit, and carbon and nitrogen flux measurements. Regional model simulations at a spatial scale of approximately 25 km are also presented. This study demonstrates that biofuel crops have higher net primary productivity than food crops due to increased solar radiation interception and radiation use efficiency. The authors also comment that the high water and nutrient efficiencies of biofuel crops lends them suitable to be grown on soils in which food crops are unable to have economic yields.

Wu, Demissie, and Yan (2012) use the SWAT (Soil and Water Assessment Tool) model to examine the water quality effects of 2015 biofuel production estimates. This study confirms that growing switchgrass reduces soil erosion and decreases nitrogen and phosphorous levels. Nelson, Ascough, and Langemeier (2006) apply the SWAT Model to the Delaware Basin Region of Kansas to determine switchgrass production potential, breakeven costs, and potential environmental impacts. The authors conclude that there are water quality related environmental advantages of producing switchgrass in lieu of traditional agricultural products.

VanLoocke, Twine, Zeri, and Bernacchi (2012) use a biophysical model, Agro-Ibis, to predict switchgrass yields. The model is validated for switchgrass at a site in Illinois. The correlation coefficient for leaf level photosynthesis is 0.87 for this study, while the correlation coefficient for leaf area index is 0.57, and modeled evapotranspiration is within 8% of observed values. Additionally, simulated yields are within one standard error of observed yields. The study also conducted yield simulations for the Midwestern United States. In addition to yield modeling, an important objective of this work was to model water use efficiency. Findings suggest that both miscanthus and switchgrass have better biome water use efficiency than maize. For harvest water use efficiency, miscanthus performs better than switchgrass, while maize and switchgrass perform similarly.

More Mechanistic Models

There are several other biogeophysical modeling studies that simulate processes such as stomatal conductance and detailed carbon and nitrogen cycling. Miguez, Maughan, Bollero, and Long (2012) present a semi-mechanistic dynamic crop yield model that simulates leaf level photosynthesis and stomatal conductance for switchgrass and miscanthus. For switchgrass, the model was tested with data from 30 previous studies and reports an index of agreement of 0.71 with a mean bias of -0.62 MG/h. The authors also project crop yields at a 32 km resolution for the years 1979-2010. Model inputs include hourly weather data. Specifically, input data for simulations in the state of Illinois are from Illinois weather stations; additional input data is from NCEP (National Center for Environmental Prediction) reanalysis data and NLDAS (NASA land data assimilation systems).

Di Vittorio, Anderson, White, Miller, and Running (2010) use Biome-BCG to simulate switchgrass growth. This effort includes detailed modeling of photosynthesis and carbon and nitrogen pools using more than 50 vegetation parameters and nine location and soil parameters. Numerical methods are employed in order to determine missing parameters. In order to generate climate data, the authors modify DAYMET, and soil data is from the USDA NRCS web soil survey. Input to this model includes observed switchgrass yield data from sites in Nebraska, Pennsylvania, and North Dakota. For the single site optimization portion of this study, the model was able to predict fifth year stand yields within a 95 percent confidence interval. The multi-site optimization predicted eleven out of fifteen of fourth year stand yields within a ninety-five percent confidence interval. An important observation of this study is that it is preferable to use more mature plant data than site average yields.

Lee et al. (2012) simulate switchgrass yields using the DAYCENT (Daily Century) model, a modified version of the CENTURY model that simulates processes such as plant productivity nutrient cycling, and soil water and temperature. DAYCENT accepts as input soil and climate data sets and predicts carbon and nitrogen fluxes. Data sources used as input for this work includes the SSURGO soil database, CIMIS for California weather, Mesonet for Oklahoma weather, and Daymet to obtain weather data for the remaining states. The model was calibrated using data from 37 field sites in the US, and the model was validated using data from sites in California. R squared values between predicted and observed switchgrass yields ranged from 0.23-0.26 for lowland ecotypes and from 0.38-0.71 for upland ecotypes. Chamberlain, Miller, and Frederick (2011) evaluate the efficacy of DAYCENT in predicting the long-term yield of switchgrass in the south. For this study, switchgrass yield predictions are within 25% of observed yields in the southern United States, and within 6% in the region in which the model is calibrated (Darlington County, South Carolina); in general, the model over predicted yields for both switchgrass and cotton. Model inputs include NRCS soil data, and Daymet and NOAA climate data. This work also includes projections of reduction in greenhouse gases when landuse is converted from cotton to switchgrass. A summary of selected studies that include simulated switchgrass yields is included in Table 3-1.

Table 3-1 Switchgrass Yield Simulations Summary

Source	Location	Ecotype	Average Yield	Variation
Tulbure, Wimberly, Boe, and Owens (2012)	US	Upland	0.5-12.74 Mg/ha,	0.04-2.41 interquartile ratio
Jager et al. (2010)	US	Upland	Roughly 3-15 Mg/ha	interquartile range -0.56-0.71, correlation between measured and predicted 0.62 training 0.58 testing
Lee et al. (2012)	US	Upland/ Lowland	2.4-41.2 Mg/ha	,Model explain 23-36% yield variation in lowland cultivar and 38-71% variation in upland cultivar
Jager et al. (2010)	US	Lowland	roughly 5-23 Mg/ha	, interqartile range-0.59-0.55, correlation between meaured and predicted 0.46 training,0.19 testing
Chamberlain, Miller, and Frederick (2011)	S US	Lowland	5-25 Mg/ha	, predictions within 25% of observed yields in the southern US
J. R. Kiniry et al. (2005)	TX,AR, LA:	Lowland	15.34 Mg/ha	SD +-3.57 Mg/ha, model accounsts for 47% of variance
Persson, Ortiz, Bransby, Wu, and Hoogenboom (2011)	AL, GA	Lowland	15.5 Mg/ha	Range: 7.45-22.9 Mg/ha RMSE 6.575 Mg/ha
Landers, Thompson, Kitchen, and Massey (2012)	NE MS & S IL	Lowland	12.56 Mg/ha	roughly 12-17 Mg/h)
Miguez, Maughan, Bollero, and Long (2012)	IL/US	Upland/ Lowland	Max 20 Mg/ha,	Index of Agreement = 0.71, mean bias -0.62 Mg/ha RMSE=4.2 Mg/ha
Landers, Thompson, Kitchen, and Massey (2012)	NE MS & S IL	Upland	8.51Mg/ha	Range: roughly 7-12 Mg/h
Jain, Khanna, Erickson, and Huang (2010)	IL	Upland	13.8 Mg/ha,	Switichgrass Modeled Yields 4% Higher than Measured
Gopalakrishnan, Negri, and Salas (2012)	IL		Roughly 10 Mg/ha	2.5 Mg/ha SD, R^2=0.94

VanLoocke, Twine, Zeri, and Bernacchi (2012)	IL		Roughly 10 Mg/ha	correlation coefficient for LAI 0.57 correlation coefficient leaf level photosynthesis 0.87 evapotranspiration within 8% of observed, within 1 SD of mean
Brown, Rosenberg, Hays, Easterling, and Mearns (2000)	Midwest		Mead, NE 9.8 Mg/ha Ames, IA 12.8 Mg/ha	Mead, NE SD 2.6 Mg/ha RSME 2.7 Mg/ha, Ames, IA: 2.3 SD Mg/ha RMSE 3.0 Mg/ha
Powers, Ascough, Nelson, and Larocque (2011)	Midwest		10.8 Mg/ha	
McLaughlin, Kiniry, Taliaferro, and Ugarte (2006)	VA,NE,TX,AL		12.3 Mg/ha	Range: 10.2-15.7 Mg/ha
Grassini, Hunt, Mitchell, and Weiss (2009)	IA, NE, TX	Upland/ Lowland	10-40 Mg/ha	1.5 Mg/ha, RMSE
Corson, Rotz, and Skinner (2007)	PA	Upland	Roughly 1-2 Mg/ha	R^2=0.117
Di Vittorio, Anderson, White, Miller, and Running (2010)	NE,PA,ND	Upland		SD = 0.59-5.86 Mg/ha, yields within -40% to 65% of observed yields

Model Descriptions

This chapter presents two models: a mechanistic model based on Beer's Law that is similar to EPIC/Almanac (but with many simplifications and alternative data sources), and a mechanistic model similar to that of Jager et al. (2010) (again with some modifications and alternative data sources). The next few sections will outline the two modeling approaches while illuminating the key differences from previous works. This will be followed by a description of the data preparation and model training and validation process. Finally, modeling results and switchgrass yield projections for the southeastern United States for 2008-2012 and 2048-2052 will be presented.

Mechanistic Model Description

Recall that Beer's law mechanistic models simulate crop development as a function of cumulative heat units, leaf area index as a function of crop development, fraction of photo synthetically active radiation intercepted as a function of leaf area index (LAI), and above ground biomass as a function of intercepted radiation (Monteith & Unsworth, 1990). For the mechanistic model presented in this chapter, fraction of photosynthetically active radiation is a function of LAI (leaf area per ground area) and parameter k that can be location and cultivar specific (**Equation 3-1**).

Equation 3-1

$$FS = 1 - \exp(-k \times LAI)$$

Note that LAI at a particular time period within the growing season is a function of relative LAI (RLAI) and the Maximum LAI (MAXLAI), a parameter that can also be location and cultivar specific (**Equation 3-2**).

Equation 3-2

$$LAI = RLAI \times MAXLAI$$

MAXLAI is the season maximum leaf area index, while RLAI is a function that represents the cumulative fraction of total season LAI observed at a particular location and time (**Equation 3-3**).

Equation 3-3

$$RLAI = \frac{FHUM_t}{FHUM_t + \exp(Y_1 - Y_2 \times FHUM_t)} \forall FHUM_t \leq 0.7$$

As in J. R. Kiniry et al. (1996), RLAI is modeled by a sigmoid curve that is a function of the fraction of heat units to maturity observed at particular location and time (FHUM). The sigmoid curve coefficients (Y_1, Y_2) are chosen such that 20% of potential LAI is reached at 10% of cumulative heat units, while 95% of potential LAI is reached at 20% of cumulative heat units; the quantity of heat units to maturity is 2300. Note that RLAI decreases linearly from the maximum value to zero after 70% of the cumulative heat units are reached (Equation 3-4).

Equation 3-4

$$RLAI = \frac{10}{3} - \frac{10}{3} \times FHUM_t \forall 0.7 < FHUM_t \leq 1$$

Table 3-2 Leaf Area Index Parameters

FS	Fraction of incoming solar radiation intercepted by leaf canopy $\frac{MJ/m^2D}{MJ/m^2D}$
k	Light extinction coefficient
LAI	Leaf area index $\frac{m^2}{m^2}$
$MAXLAI$	Crop Specific Maximum LAI $\frac{m^2}{m^2}$
$RLAI$	Relative Leaf Area Index (LAI)

$FHUM_t$	Fraction of Heat Units from Annual Growth initiation (AGI) to maturity as observed on day t $\frac{m^2}{m^2}$
Y_1, Y_2	Sigmoid Curve Coefficients

Unlike Kiniry, Sanderson et al. 1996, for the model presented in this chapter, heat units begin to accumulate at the date of AGI (Annual Growth Initiation), not planting date. The date of AGI is defined according to Grassini et al. (2009). That is, AGI is the first day of the year for which the fifteen day running average temperature is greater than or equal to 13 degrees (Equation 3-5, Equation 2-7, Equation 2-8, Equation 2-9).

Equation 3-5

$$if\ \left(AGI = \emptyset \wedge \sum_{t'}^{T} \frac{Temp_t^{Avg}}{15} \geq 13℃\right)\ then\ AGI\ is\ replaced\ by\ t$$

Equation 3-6

$$if\ \left(AGI = \emptyset \wedge \sum_{t'}^{T} \frac{Temp_t^{Avg}}{15} < 13℃,\right)\ then\ AGI\ remains\ \emptyset$$

Equation 3-7

$$(if\ AGI \neq \emptyset\ )\ then\ AGI\ remains\ unchanged\ for\ the\ remainder\ of\ the\ season$$

Equation 3-8

$if\ T \geq 15, t' = T - 15, if\ T < 15, t' = t_0$, where t_0 is the first day of the calendar year

After the date of AGI, the heat unit calculations begins. Cumulative heat untis are calculated based on daily temperature (Equation 2-10). At temperature lower than 12℃, no heat untis are accumulated, and daily heat unit accumlation is capped at 25℃.

Equation 3-9

$$if\ 12℃ < Temp_t^{Avg} < 25℃ \wedge AGI\ \neq \emptyset, CHU_t = CHU_{t-1} + Temp_t^{Avg}$$

$$if\ Temp_t^{Avg} \geq 25℃ \wedge AGI\ \neq \emptyset, CHU_t = CHU_{t-1} + 25℃$$

$$else\ CHU_t = 0$$

Additionally, the current stand development stage, or fraction of heat units maturity is calculated by dividing the cuumlative heat units by the heats units to maturity (Equation 3-10).

Equation 3-10

$$FHUM_t = \frac{CHU_t}{HUM}$$

$HUM = 2300$, (J. R. Kiniry et al., 1996)

Table 3-3 Heat Units to Maturity Parameters

AGI	Annual Growth Initiation date
t	Day of year
$Temp_t^{Avg}$	Average Temperature on day t ℃
CHU_t	Cumulative heat units as observed at t℃
HUM	Cumulative heat units at maturity ℃

So far this chapter has discussed the components of Equation 2-1, the fraction of intercepted solar radiation at a particular location and time in detail. However, the ultimate objective is to arrive at an estimation of biomass yield at each location. Thus, intercepted solar radiation is converted to daily intercepted biomass using the radiation use efficiency parameter as show in Equation 3-11. That is, the daily intercepted biomass is a function of fraction of intercepted solar radiation, radiation use efficiency, daily photsynthetically active radiation, and day length.

Equation 3-11

$$Y_t = RUE_{FHUM_t} \times D \times PAR \times [1 - \exp(-k \times LAI)]$$

Photosynethially active radiation is a function of daily incoming solar radiation, and fraction of solar radiation that is intercepted by leaf canopy.

Equation 3-12

$$PAR = SR \times FSR$$

$FSR = 0.45$, (J. R. Kiniry et al., 1999)

Also note that according to J. R. Kiniry, Tischler, and Van Esbroeck (1999) and J. R. Kiniry et al. (1996), like LAI, radiation use efficiency decreases linearly to zero after reaching seventy percent of the cumulative heat units to maturity.

Equation 3-13

$$RUE_{FHUM_t} = 0.047\left(\frac{Mg}{H}\right)\left(\frac{m^2}{MJ}\right) \forall\ FHUM_t\ \leq 0.7$$

$$RUE_{FHUM_t} = \left[\frac{10}{3} - \frac{10}{3} \times FHUM_t\right] \times 0.047\left(\frac{Mg}{H}\right)\left(\frac{m^2}{MJ}\right) \forall\ 0.7\ < FHUM_t \leq 1$$

Note also that day length is calculated according to Forsythe et al. (1995).

Equation 3-14

$$D = 24 - \frac{24}{\pi}\cos^{-1}\left[\frac{\sin\frac{p\pi}{180} + \sin\frac{2\pi}{180}\sin\varphi}{\cos\frac{2\pi}{180}\cos\varphi}\right]$$

$$\theta = 0.2163108 + 2\tan^{-1}[0.9671396\tan[0.00860 \times (t - 186)]]$$

$p = 0.833\ degrees$, (Forsythe, Rykiel, Stahl, Wu, & Schoolfield, 1995)

Table 3-4 Intercepted Biomass Equation Details

Y_t^p	Intercepted Biomass on day t, $\frac{Mg}{H}$
RUE_{FHUM_t}	Radiation Use Efficiency as a function of cumulative heat units $\left(\frac{Mg}{H}\right)\left(\frac{m^2}{MJ}\right)$
D	Day Length (Hrs)
PAR	Photosynthetically Active Radiation $\frac{MJ}{m^2 Day}$
SR	Incoming Solar Radiation $\frac{MJ}{m^2 Day}$

In this formulation biomass growth is limited by soil moisture deficit. Thus, soil moisture limitations are modeled using a simple linear relationship similar to that of Steduto (2012). However, instead of calculating evapotranspiration deficit directly, the ratio of soil water to soil available water holding capacity is calculated (Equation 3-15). This is a great simplification to the soil water balance routines presented in EPIC/ALMANAC. A rooting depth of 2m is assumed as in Grassini et al. (2009) and J. R. Kiniry et al. (1999).

Equation 3-15

$$\left(1-\frac{Y_t^p}{Y_t}\right)=K(1-FAWHC)$$

$$FAWHC=\frac{SW}{RAW}$$

$$RAW=\ \rho TAW$$

$$TAW=(FC-WP)$$

$$\rho=0.5$$

Table 3-5 Soil Moisture Limitation Equation Details

Y_t^p	Predicted Biomass Yield (Mg/H)
Y_t	Predicted Biomass Yield Under Non Moisture Limiting Conditions (Mg/H)
K	Crop coefficient (mm/day)/(mm/day)
$FAWHC$	Fraction of Available Water Holding Capacity (kg water/m^3 soil)
SW	Soil Water (kg water/m^2 soil)
RAW	Readily Available Water (m)
FC	Field Capacity (m^{3}water/ m^{3}soil)
WP	Wilting Point (m^3 water / m^3 soil)

Finally, the full season yield is the sum of daily intercepted biomass adjusted for soil moisture limitations as outlined in Equation 3-16. Note that the previous equations force Y_t^p to zero for days prior to AGI, and for days after maturity.

Equation 3-16

$$Y_{season}^p = \sum_{t=1}^{365} Y_t^p$$

Table 3-6 Predicted Biomass Equation Details

Y_t^p	Predicted Daily Intercepted Biomass (MG/h)
Y_{season}^p	Full season Predicted Biomass Yield

Light Extinction Coefficient/Maximum Leaf Are Index Parameter

The previous equations do not include explicit parameter values for light extinction coefficient, maximum leaf area index, and crop coefficients representing crop yield response to soil moisture deficit. These cultivar and site-specific parameters were determined numerically during the model training process and were examined for reasonableness using the range of values reported in the literature. When the fraction of incoming solar radiation intercepted by leaf canopy equation is presented in a slightly different form, as in Equation 3-17, it clear that it is difficult distinguish light extinction coefficient from maximum leaf area index numerically. Thus, the product of maximum leaf area index and light extinction coefficient is lumped into one parameter in this model.

Equation 3-17

$$FS = 1 - \exp(-k \times RLAI \times MAXLAI)$$

Values for the parameter representing the product of maximum leaf area index and light extinction coefficient for various cultivars are included Table 3-7.

Table 3-7 Mechanistic Model Parameters

	Parameter Value
All Cultivars	-0.99
Lowland	-1.53
Upland	-0.92

J. Kiniry et al. (2011) includes a study of the maximum leaf area index and light extinction coefficient parameters. Maximum leaf area index ranges from [2.9 22], and the light extinction coefficient ranges from [-.23 -1.1] depending on cultivar and location of measurement.

Crop Coefficient, K

According to Steduto (2012), the crop coefficient K, which models crop yield response to soil moisture deficit, can actually vary throughout the season. Thus, multiple crop coefficient parameters are included in this model based on day of year ranges

Specifically, if no more than 80 days have elapsed in a particular year, the crop coefficient K_1 is used. If more than 100 days, but no more than 120 days have elapsed, crop coefficient K_2 is used. If more than 140 days have elapsed in a particular year, then crop coefficient K_3 is used. For all other day of year ranges, the crop coefficient was determined to be zero. The crop coefficient values are included in Table 3-8.

Table 3-8 Crop Coefficient Parameter Values

	K_1	K_2	K_3
All Cultivars	0.89	0.09	1.2
Lowland	1.18	0.22	0.32
Upland	0.84	1.42	0.93

Yield Model Calculation Steps

Since the yield model calculation begins at the date of AGI, the first step in the yield model calculation procedure is to determine this date from average daily temperature values using Equation 3-5, Equation 3-6, Equation 3-7, and Equation 3-8. At the date of AGI, the calculation of cumulative heat units and fraction of heat unit to maturity from daily temperature values begins using Equation 3-9 and Equation 3-10 respectively. Next relative leaf area index as a function of fraction of heat units to maturity is calculated using Equation 3-3 and Equation 3-4; leaf area index is calculated according to Equation 3-2. Radiation use efficiency also depends on the fraction of heat units maturity and can be calculated using Equation 3-13.

Solar radiation data, measured in $\frac{MJ}{m^2 Day}$ is used to calculate photosynthetically active radiation (Equation 3-12). In order to derive daily photosynthetcically active radiation, daylength is also calculated (Equation 3-14). Daily intercepted biomass under non-moisture limiting conditions can then be calculated using equation Equation 3-11. Next, daily soil moisture data is used to calculate daily intercepted biomass under moisture limiting conditions (Equation 3-15). Finally daily intercepted biomass is summed in order to derive full season yields using Equation 3-16. An overall diagram for the mechanistic model is included in Figure 3-1.

Figure 3-1 Yield Model Flowchart

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Empirical Model Formulation

Recall that the empirical model presented in this study is similar to that of Jager et al. (2010) with a few modifications. These modification include the elmination of the harvest frequency and stand age parameters in addition to the use of the fraction of available soil available water holding capacity in lieu of the soil moisture index parameter from Jager et al. (2010). This is expressed inEquation 3-18.

Equation 3-18

$$Y_{season}^{p} = C_0 + C_1\bar{T} + C_2\bar{T}^2 + C_3T_{min} + C_4P^{tot} + C_5P^{tot}\bar{T} + C_6\bar{W}$$

Table 3-9 Empirical Model Equation Details

$\bar{T}$	Season Average Temperature (April-September) ℃
T_{min}	Season Minimum Temperature (April-September) ℃
P^{tot}	Season Total Precipitation (April-September) (mm)
$\bar{W}$	Season Average Fracation of Available Water Holding Capacity (April-September) mm/mm

As in the mechanistic case, separate models for upland, lowland, and both upland and lowland cultivars are included in this work. Model selection is conducted using the boostrapping method of leave one out cross validation. Model parameters for the empirical models are listed in Table 3-10. As in the mechanistic model, inputs data are from the NARR model and the Dunne soil data set. Season average termperature, precipitation, and soil moisture are calculated by aggregating daily values from NARR model output at a 32 km spatial resolution.

Table 3-10 Empirical Model Parameters

	C_0	C_1	C_2	C_3	C_4	C_5
Upland/Lowland	10.3784	0.6611	-0.0256	0.0433	0.0218	-0.0009
Lowland	-62.6039	7.595	-0.1836	0.2236	0.0072	-0.0002
Upland	-27.9069	4.4921	-0.1224	0.0857	0.0092	-0.0004

Model Training and Validation:

Most of the input data required for the mechanistic model is readily available from the North American Regional Reanalysis (NARR) model at a 32 km grid resolution. Input parameters from NARR used in the mechanistic model portion of this study include daily 2m air temperature, soil moisture, and downward shortwave solar radiation. Parameters required for calculating fraction of soil available water holding capacity (field capacity and wilting point) are from the Dunne soil set (Dunne & Willmott, 1996).

In order to train both the mechanistic and empirical models described in this chapter, a switchgrass field trial database was obtained (Wullschleger et al., 2010), which included 600 upland cultivar and 459 lowland cultivar observations, spanning 30 locations, the majority of which are within the southeastern United States. The area of study for the modeling work presented in this thesis include, Texas, Georgia, Alabama, Arkansas, Louisiana, Oklahoma, Tennessee, North Carolina, South Carolina, and Florida. The few points from the database outside of this region of study were not included in the model training efforts.

Within the field trial database there were some instances of multiple data points at the same location in a particular year. For these cases, the mean among the available observations is used. The resulting data set includes 79 distinct location year combinations for the upland cultivar and 54 location year combinations for the lowland cultivar with observation years spanning 1989-2001. Cubic spline interpolation was employed to interpolate weather and soil variables to field trail data points, and the model was trained using leave one out validation for upland cultivars, lowland cultivars, and a case in which both cultivars are included.

Results:

For both the empirical and mechanistic models, parameters were obtained by a bootstrapping method and leave one out model cross validation. Using this method, models are trained *k* times, once for each of the available data points. At each of the *k* iterations, the parameters selected minimize squared error (SSE) between predicted total season yield, and actual total season yield for each of the location and years in which data is available. This is expressed in equation Equation 3-19. Values of SSE are compared among iterations, and the model which yields the lowest SSE among all iterations is selected.

Equation 3-19

$$SSE = \left(\sum_{i,season} Y^{p}_{i,season} - Y^{a}_{i,season} \right)^{2}$$

Where:

SSE	Sum squared Error
$Y^{p}_{i,season}$	Predicted Full season yield at location *i*
$Y^{a}_{i,season}$	Actual Season Yield at location *i*

For cases in which multiple yield measurements were available at particular locations $Y^{a}_{i,season}$ is the mean of all available measurements at location *i* for a particular season. Pearson correlation coefficients between meaured and predicted yields and root mean squared error for both the mechanistic and statistical models are included in Table 3-11.

Table 3-11 Model Selection, Goodness of Fit, and Error

	Root Mean Squared Error	Pearson Correlation Coefficient Training	Pearson Correlation Coefficient Testing
Mechanistic Upland/Lowland	3.60	0.46	0.41
Mechanistic Lowland	5.10	0.49	0.46

Mechanistic Upland	3.54	0.79	0.75
Empirical Upland/Lowland	3.65	0.43	0.39
Empirical Lowland	5.05	0.50	0.47
Empirical Upland	3.46	0.80	0.77

Once the switchgrass yield models were parameterized, 34 years (1979-2012) of switchgrass yields were projected at a spatial resolution of 32 km. Instead of only using data for the years and locations in which field trail data was available as in the model training phase, switchgrass yields are simulated for the entire southeastern region for all locations and years in which NARR daily climate model output was available. An available cropland acres dataset, derived from the 2001 Landsat Landcover Dataset, was obtained through personal communication with Tony Giarrusso (Geographic Information Systems, Georgia Institute of Technology). This datasets is used alongside the yield projections to ensure that projected yields are zero in grid points in which the available cropland acres are zero.

In order to consider the potential effects of climate change, switchgrass yield simulations for the years 2048-2052 at a spatial resolution of 36 km were conducted. The variables required by the yield model (equivalent to those from NARR) were obtained from Liu Peng, and Dr. Anthanasios Nenes (Department of Chemical and Biomolecular Engineering/Earth and Atmospheric Science, Georgia Institute of Technology), who used the Weather Research Forecast model (WRF) for their analysis. Average yield projections for empirical and mechanistic models for lowland and upland cultivars in both current and future climate scenarios are including in Figure 3-2 and Figure 3-3 respectively. In both figures, yields are pictured by percentile. For example, locations with average yields that are less than or equal to the 25th percentile of all yields in the region of study are represented by white squares. Locations with average yields that fall between the 25th percentile and median are pictured by light gray squares, while dark gray squares represent the median to 75th percentile; remaining locations are pictured by black squares.

Figure 3-2 1978-2012 Yield Projections

☐ Minimum to 25th Percentile
▒ 25th Percentile to Median
▓ Median to 75th Percentile
■ 75th Percentile to Maximum

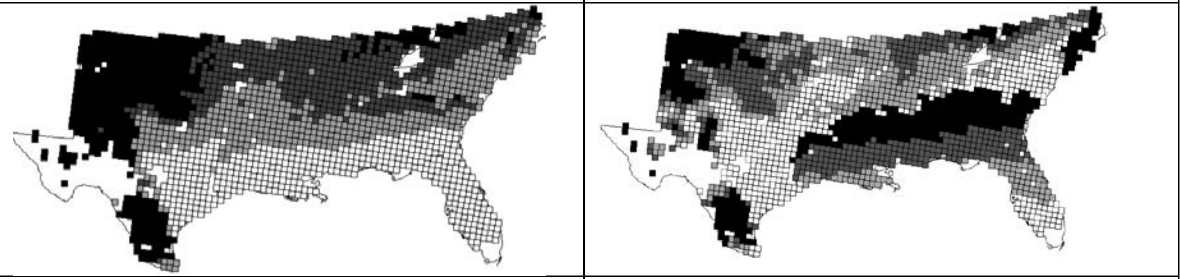
Mean Yield (1978-2012) Mechanistic Lowland | Mean Yield (1978-2012) Mechanistic Upland

Mean Yield (1978-2012) Empirical Lowland | Mean Yield (1978-2012) Empirical Upland

Figure 3-3 Yield Projections, 2048-2052

□ Minimum to 25th Percentile
▒ 25th Percentile to Median
▓ Median to 75th Percentile
■ 75th Percentile to Maximum

Mean Yield (2048-2052) Mechanistic Lowland | Mean Yield (2048-2052) Mechanistic Upland



Mean Yield (2048-2052) Empirical Lowland | Mean Yield (2048-2052) Empirical Upland

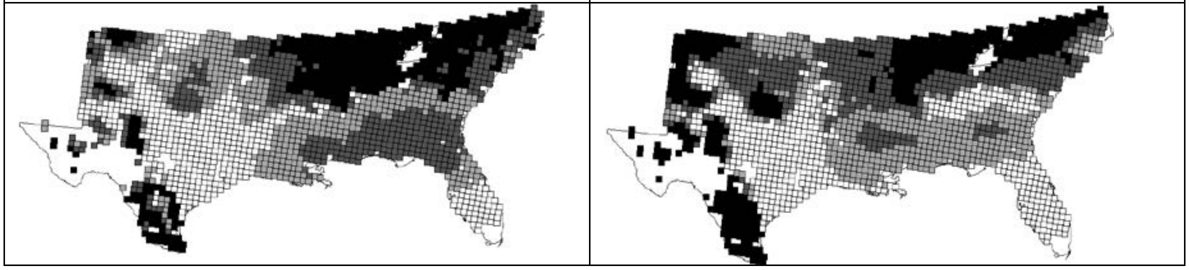


Table 3-12, Table 3-13, Table 3-14, and Table 3-15 include the percentiles corresponding to the average yields picture in Figure 3-2 and Figure 3-3. The tables also include percentiles for 2008-20012 and 2048-2052 so that a 5 year period in the current climate scenario can be compared to five year period in the future climate scenario.

Table 3-12 Summary Statistics for Theoretical Model, Lowland Cultivar (Mg/h)

	Theoretical Lowland			
	25th Percentile	Median	75th Percentile	Maximum
Average (1978-2012)	16.13	17.04	17.93	22.71
2008	16.87	17.91	19.24	22.91
2009	15.90	17.22	18.48	23.82
2010	15.68	16.82	18.34	22.37
2011	15.24	17.27	18.78	22.76
2012	12.67	16.04	17.70	24.84
2048	14.35	16.19	17.31	26.25
2049	14.10	16.19	17.68	26.80
2050	13.82	16.39	17.44	25.27
2051	14.35	16.33	17.33	24.94
2052	13.61	16.27	17.09	25.48
Average (2048-2052)	13.96	16.32	17.22	25.75

Table 3-13 Summary Statistics for Theoretical Model, Upland Cultivar (Mg/h)

	Theoretical Upland			
	25th Percentile	Median	75th Percentile	Maximum
Average (1978-2012)	5.50	8.47	11.06	17.09
2008	7.73	9.83	12.29	17.29
2009	7.56	10.12	12.31	17.95
2010	7.60	10.28	11.64	16.78
2011	4.88	7.55	10.35	17.14
2012	4.81	6.65	8.68	18.49
2048	7.96	9.07	10.28	19.44
2049	8.13	9.33	10.62	19.97
2050	8.16	9.04	10.17	16.20
2051	7.90	9.04	10.64	17.25
2052	8.06	9.07	10.22	18.65
Average (2048-2052)	8.12	9.12	10.34	18.30

Table 3-14 Summary Statistics for Empirical Model, Lowland Cultivar (Mg/ha)

	Empirical Lowland			
	25th Percentile	Median	75th Percentile	Maximum
Average (1978-2012)	12.47	13.50	14.44	16.78
2008	13.35	14.30	15.09	17.17
2009	13.62	15.14	15.89	17.99
2010	9.10	10.60	12.12	15.91
2011	6.08	9.69	11.79	17.36
2012	9.82	11.75	13.15	16.83
2048	14.54	15.52	16.27	18.46
2049	14.55	15.94	17.00	19.30
2050	12.47	13.69	14.49	18.36
2051	12.06	13.54	14.40	18.78
2052	14.22	15.17	16.34	19.35
Average (2048-2052)	13.78	14.80	15.64	18.66

Table 3-15 Summary Statistics for Empirical Model, Upland Cultivar (Mg/ha)

	Empirical Upland			
	25th Percentile	Median	75th Percentile	Maximum
Average (1978-2012)	6.86	8.82	10.42	16.35
2008	7.29	9.01	10.61	14.88
2009	8.14	10.72	12.40	15.87
2010	4.18	5.99	7.86	15.23
2011	3.43	5.16	7.36	15.58
2012	4.39	6.26	7.65	16.32
2048	8.1525	9.765	11.2	16.36
2049	8.8425	10.47	11.74	17.19
2050	7.96	9.03	9.945	17.04
2051	6.8525	8.3	9.1675	16.74
2052	8.31	9.66	11.06	16.92
Average (2048-2052)	8.36	9.15	10.583	16.796

Discussion and Conclusion:

The correlation coefficients displayed in Table 3-11 are the correlation between observed and predicted yields. These results can be compared to that of Jager et al. (2010), who report overall correlation coefficients across all sites. Recall that Jager et al. (2010) report upland cultivar correlation coefficients of 0.62 and 0.58 are reported for training and testing data respectively. For lowland varieties, Jager et al. (2010) report correlation coefficients of 0.46 and 0.19 respectively. Table 3-11 shows this work makes slight improvements to these numbers across all models considered. Recall also that Persson, Ortiz, Bransby, Wu, and Hoogenboom (2011) evaluated the ALMANAC model and report an overall root mean square error of 6.6 Mg/ha. Again, Table 3-11 indicates moderate improvements on this statistic across all models examined in this study. The models presented in this paper demonstrate good performance and are also relatively easy to implement. The majority of the input data required for both the mechanistic and empirical models can be obtained from the North American Regional Reanalysis model, which provides data at 32 km resolution. In addition to the climate model output; the only other required data set is the Dunne soil set

Table 3-12, Table 3-13, Table 3-14, and Table 3-15 indicate that lowland cultivars experience higher yields than that of upland cultivars. When comparing current climate scenario to future climate scenario, it seems that future projections indicate lower median yields for future climate scenarios. Model fit appears to be roughly equivalent for the empirical and mechanistic models. However, the models are fundamentally different and Figure 3-2 and Figure 3-3 indicate that the spatial distribution of crop yields vary significantly between the empirical and mechanistic models.

Despite similar model fit, one could argue that mechanistic models might be preferable to the empirical model as the mechanistic model models real physical processes and contains parameters that can easily be improved or altered based on new site specific or cultivar specific information. For example, locally measured light extinction coefficients and maximum leaf are index parameters for particular cultivars could easily be inserted in the mechanistic model when available. Other parameters such as radiation use efficiency, heat units to maturity, and soil moisture response parameters are also physically meaningful parameters that could be updated when better information is available.

Overall, it has been shown that climate model output data can be used to train, test, and simulate switchgrass yields for large geographic areas for both upland and lowland cultivars. Both mechanistic and empirical models can be used for this application, and the use of climate model soil moisture data can be used to greatly simplify mechanistic models by eliminating the need to implement complex soil water balances. In addition, climate model output data can also be used to simulate switchgrass crop yields in current and future climate scenarios. Future extensions of this work may include examining more climate scenarios. Other extensions might also include the use of measured cultivar and site-specific parameters such as leaf area index, light extinction coefficient, and heat units to maturity.

CHAPTER 4 Multi Period Optimization Problem

Two biorefinery supply chain designs were considered in Chapter2. The first design includes the use of fixed centralized processing facilities that convert biomass into a crude bio oil via fast pyrolysis. Biomass is transported from harvest location to processing facilities. Once the biomass is processed, crude bio-oil is transported to a large refinery for final processing, which could include upgrading to a transportation grade fuel. The alternative design includes the use of mobile processing units that move from harvest location to harvest location and perform the initial processing steps. In this chapter, multi period designs are compared for both current and future climate scenarios in the presence of uncertainty in switchgrass yield.

The optimization problems presented in previous chapters are single stage mixed integer linear programming models (MILP) with economic objective functions. However, the models presented in this chapter are two-stage multi scenario planning problems that maximize the net present value of the first stage decisions and the expected value of the second stage decisions. In the case study presented in this chapter, switchgrass planting decisions are considered first stage decisions. Since switchgrass is a perennial crop, planting decisions are conducted at the beginning of the planning period, and crop yields are realized throughout the planning horizon. The per hectare switchgrass yields that are realized during the planning horizon depend on annual weather conditions, but the hectares planted remain constant throughout the planning horizon. For the fixed processing case, the size and location of biorefineries is fixed throughout the planning period, and it is thus considered a first stage decision. However, for the mobile processing case, processing capacity is considered to be a second stage decision, and it is not fixed throughout the planning horizon, because it is assumed that the nature of the mobile processing design lends itself to being flexible to adjusting processing capacity each season. This inherent flexibility of the mobile processing design could potentially prove advantageous as the mobile processing design could perform better under uncertainty.

Previous Multi Period Biorefinery Network Studies

There are several studies in the literature that present optimization models for the renewable energy supply chain problem under uncertainty. For example, Kim, Lee et al. (2008) present a hydrogen infrastrucutre model under demand uncertainty. The authors present a two stage cost minimization model in which the objective is to minimize the total daily cost for the first stage, and the expected value of the second stage. The case study presented includes Korea divided into 16 regions. Interesting findings of this work are that hydrogen transportation mode decisions differ greatly when uncertainty is introduced.

Dal-Mas, Giarola et al. (2011) used a MILP model to study uncertainties in production costs and selling price for ethanol production. The case study presented includes Northern Italy modeled as 50 homogenous squares. Model decisions include the location of biomass production sites, biofuel production facilities location and scale, and biofuel demand satisfaction rate. Supply chain decisions such as how biofuel is distributed to blending terminals and how biomass is distributed to production facilities are also modeled. Both profit driven and financial risk driven optimizations are conducted. Specifically, the authors maximize expected NPV using the probability of various biomass cost and biofuel price scenarios. They also present an optimization model in which NPV is maximized when only worst market scenarios are considered (risk minimization approach). Important findings are that profit can be achieved for the expected NPV maximization model even when the prices of revenue generating byproducts decrease. However, for the worst-case optimization, market entry is only advised for scenarios in which the selling price of revenue generating byproducts is very high.

Almansoori and Shah (2012) built a multi-period planning model to study the hydrogen supply chain, an extension of a previous work (Almansoori and Shah (2009)) that designed a hydrogen supply chain for mainland Britain. Decisions in this study include mode of transportation and transportation links, production rate, storage decisions, hydrogen flow rates, and energy sources. This work formulates a three-stage stochastic optimization model in which demand is fixed in the first stage, and demand uncertainty is experienced in the second stage. A single scenario is assessed in stage one, and at each subsequent stage, each scenario branches out into three scenarios, for a total of nine scenarios by stage three. The objective is to minimize the cost of the first stage, and the expected cost of the following stages. The authors present a case study covering Great Britain in which Great Britain is divided into 45 squares of equal size. Important findings of this work include the realization that the cost and design of the supply chain network can be greatly impacted by the introduction of uncertainty.

Kim, Realff et al. (2011) use a MILP to model a biorefinery network in the southeastern United States to produce bio-diesel via Fast Pyrolysis and Fisher Tropsch conversion under uncertainty using realistic input data sets. This work models the transportation of biomass to conversation facility, the location, scale, and technology for biomass conversion as well as the distribution of final fuel products. Scenarios for this study are constructed by first determining the parameters that had the greatest effect on NPV under a single scenario by performing range analysis on the parameters of interest. Parameters deemed important by range analysis are varied +-20%, and scenarios are created. Finally, a robustness analysis and a monte carlo based global sensitivity analysis is conducted in which the single scenario approach is compared to the multi scenario models. Findings demonstrated that the multi scenario optimization was capable of minimizing the effects of uncertainty.

Optimization Model Description:

In the case study presented here, the economic implications of moving harvested biomass vs. moving mobile processing units in the presence of uncertainty in biomass yields are explored. Much of the notation for the multi-period problem is equivalent to the optimization problem presented in Chapter II, with the exception of the index *c*, which represents crop yield scenarios. Additionally, the objective function is updated such that the net present value of stage of one decisions and the expected value of stage two decisions are maximized.

Optimization Model Formulation

Table 4-1 Optimization Model Indices

i	Network locations
k	Resource
a	Maximum harvest scenario
t	Time (months)
c	Weather year scenario
f	Final Processing Location

Table 4-2 Optimization Model Sets

P_k	Set of tasks *p* that produce resource *k*
$\overline{P_k}$	Set of tasks *p* that consume resource *k*
H_t	Set of time periods that define the current harvest season as observed in period *t*
J_k	Set of incoming transfer tasks
$\bar{J}_k$	Set of outgoing transfer tasks
L	Set pipeline accessible harvest locations
R	Set of non pipeline accessible harvest locations
F	Set of locations at which final processing takes place

Table 4-3 Optimization Model Resources

k_1	Planted Land
k_2	Harvested Switchgrass
k_3	Pyrolysis Oil
k_4	Char Byproduct
k_5	Gas Byproduct
k_6	Small Mobile Unit
$\overline{k_6}$	Small Mobile Unit Before Startup
$\overline{\overline{k_6}}$	Small Mobile Unit After Startup
k_7	Medium Mobile Unit
$\overline{k_7}$	Medium Mobile Unit Before Setup
$\overline{\overline{k_7}}$	Medium Mobile Unit After Setup
$k_{x\ldots y}$	Subset of resources with subscripts between x and y (inclusive).

Table 4-4 Optimization Model Tasks

p_1	Plant Switchgrass
p_2	Harvest Switchgrass
p_3	Start Process Small Mobile Unit
p_4	Start Process Medium Mobile Unit
p_5	Process Small Mobile Unit
p_6	Process Medium Mobile Unit
p_7	Wait Small Mobile Unit
p_8	Wait Medium Mobile Unit
p_{9-12}	Process Centralized

$P_{x\ldots y}$	Subset of tasks with subscripts between x and y (inclusive)

Table 4-5 Optimization Model Variables

B_{iptc}	Extent of task *p* that starts at location *i* in time *t and scenario c*
S_{iktc}	The amount of material *k* that is stored at location *i* in time *t and scenario c*
N_{iptc}	Number of integer resources that start task *p* at location *i* at time period *t and scenario c*
$N_{i'iktc}$	Number of mobile resource of type *k* that begin moving from location *i'* to location *i* at time *t and scenario c*
$M_{i'iktc}$	Quantity of resource *k* that is transported from location i' to location *i* at time *t and scenario c*
S_{iktc}	Amount of resource *k* at location *i* as observed in time period *t* and scenario c
N_{iktc}	Number of integer resource *k* at location *i* as observed in time period *t and scenario c*
N_k^T	Total number of integer resource k
W_{ip}	Integer variable that signifies the number of biorefineries of capacity *p* that are located at candidate refinery *i*
V_{ip}	Per unit revenue generated from the execution of task & task type pair at location *i*
NPV	Net present value of the project over the planning horizon

B_{ipt}	Extent of task *p* that starts at location *i* in time *t*
S_{ikt}	The amount of material *k* that is stored at location *i* in time *t*
N_{ipt}	Number of integer resources that start task *p* at location *i* at time period *t*
$N_{i'ikt}$	Number of mobile resource of type *k* that begin moving from location *i'* to location *i* at time *t*
$T_{i'ikt}$	Quantity of resource *k* that is transported from location i' to location *i* at time *t*
S_{ikt}	Amount of resource *k* at location *i* as observed in time period *t*
N_{ikt}	Number of integer resource *k* at location *i* as observed in time period *t*
N_k^T	Total number of integer resource k
W_{ip}	Integer variable that signifies the number of biorefineries of capacity *p* that are located at candidate refinery *i*
V_{ip}	Per unit revenue generated from the execution of task & task type pair at location *i*
NPV	Net present value of the project over the planning horizon

Table 4-6 Optimization Model Parameters

SL_k	Storage loss associated with storing resource *k* for one time period
β_i	Available cropland acres at location *i*
Y_{ikc}	Yield of crop *k* at location *i* under crop yield scenario *c*
ρ_{ipkt}	Amount of resource *k* produced at location *i* per instance of task *p* at time *t*
$\tau_{i'ik}$	Time required for resource *k* to travel across arc *i'i*
$\tau_p/\overline{\tau_p}$	Time required for task *p* to produce/consume material
Max_p	Capacity of task *p*
Max_{pa}	Capacity of task and task type pair *p* under maximum planting fraction scenario *a*
Max_k	Capacity/Maximum Quantity of resource k
$\mathrm{Max}_{i'i}$	Flow capacity on arc i′i
$\mathrm{D}_{i'i}$	Distance from location i' to location *i*
$CV_{i'ik}$	Variable cost associated with transporting resource *k* from location *i'* to location *i*
CF_k	Fixed cost of equipment associated with the production of resource k
CV_p	Variable Cost associated with the execution of task *p*
CV_{ilk}	Variable Transportation Costs associated with transporting resource *k* from location *i* to its corresponding pipeline terminal *l*

CV_{lrk}	Variable Transportation Costs associated with transporting resource *k* from pipeline location *l* to refinery *r*
VE_k	Value of product *k*
YP_k	Percent Yield of resource *k* (dry input basis)

Table 4-7 Optimization Model Parameter Values

SL_k	Storage loss associated with storing resource *k* for one time period
β_i	Available cropland acres at location *i*
Y_{ikc}	Yield of crop *k* at location *i* under crop yield scenario *c*
ρ_{ipkt}	Amount of resource *k* produced at location *i* per instance of task *p* at time *t*
$\tau_{i'ik}$	Time required for resource *k* to travel across arc *i'i*
$\tau_p/\overline{\tau_p}$	Time required for task *p* to produce/consume material
Max_p	Capacity of task *p*
Max_{pa}	Capacity of task and task type pair *p* under maximum planting fraction scenario *a*
Max_k	Capacity/Maximum Quantity of resource k
$\mathrm{Max}_{\mathrm{i'i}}$	Flow capacity on arc i'i
$\mathrm{D}_{\mathrm{i'i}}$	Distance from location i' to location *i*
$CV_{i'ik}$	Variable cost associated with transporting resource *k* from location *i'* to location *i*
CF_k	Fixed cost of equipment associated with the production of resource k
CV_p	Variable Cost associated with the execution of task *p*
CV_{ilk}	Variable Transportation Costs associated with transporting resource *k* from location *i* to its corresponding pipeline terminal *l*
CV_{lrk}	Variable Transportation Costs associated with transporting resource *k* from pipeline location *l* to refinery *r*
VE_k	Value of product *k*
YP_k	Percent Yield of resource *k* (dry input basis)

L_{k_2}	0.83% per month (Sokhansanj, Mani et al. 2009)
β_i	Determined by s cropland database (acres)
Y_{ik_2c}	Yield of crop k_2 at location *i* under crop yield scenario *c*, generated by applying spatially explicit switchgrass crop yield model at location *i*, using land and atmospheric conditions from weather year *c*
$\rho_{i\bar{p}kt}$	1 for all tasks
$\rho_{ip_1k_1t}$	1
$\rho_{ip_2k_2t}$	The product of $\mathrm{Y_{ik_2c}}$ and $\mathrm{\beta_i}$ adjusted for each time period t based on switchgrass seasonality; expressed in tons
$\rho_{ip_{3-6}k_3t}$; $\rho_{ip_{9-12}k_3t}$	0.8 (Kim, Realff, Lee 2011)
$\rho_{ip_{3-6}k_4t}$; $\rho_{ip_{9-12}k_4t}$	0.1(Kim, Realff, Lee 2011)
$\rho_{ip_{3-6}k_5t}$; $\rho_{ip_{9-12}k_5t}$	0.1(Kim, Realff, Lee 2011)
$\tau_{i'ik}$	0
$\tau_{p_1}/\overline{\tau_{p_1}}$	12/120
$\tau_p/\overline{\tau_p}$	1/0 for tasks $\{\mathrm{p_{2-}p_{14}}\}$
Max_{p_5}	1500 tons per month (adjusted from Badger 2011)
Max_{p_6}	3000 tons per month (Badger 2011)
Max_{p_3}	2600 tons per month (Badger 2011 adjusted for setup time according to Polagye, Hodgson, eta al. 2007)
Max_{p_4}	1300 tons per month (Badger 2011 adjusted for setup time according to Polagye, Hodgson, eta al. 2007)
$Max_{p_{9-12}}$	1.2 Million – 4.9 Million tons per year (Kim, Realff, Lee 2011)
$Max_{k_1a_1}$	1%-20% of available cropland depending on scenario
$Max_{i'i}$	Equals 1 if distance between location pairs is less than 100 miles; Calculated in ArcMap using Multimodal Transportation Network Dataset (MMNET)
$Max_{k_{6\ldots7}}$	0
$D_{i'i}$	Calculated in ArcMap using MMNET Dataset

$CV_{i'ik}\ \forall\ k \in K_m$	(\$/mile) Calculated using $D_{i'i}$ and parameters from Polagye, Hodgson et al. 2007
$CF_{k_{6-9}}$	From Badger 2011, adjusted using for 0.6 scale factor
$CV_{i'ik_{3-6}}$	Calculated using $D_{i'i}$ and transportation costs per ton-mile values from (Kim, Lee, Realff 2011)
$CF_{p_{9-12}}$	(\$/year from Kim, Lee, Realff 2011)
$CV_{p_{9-12}}$	(\$/ton from Kim, Lee, Realff 2011)
$CV_{p_{3-6}}$	\$15.6/ton (from mobile unit thermal and electric utility needs from Badger 2011, and grass specific material balance from Kim, Lee, Realff 2011)
VE_{k_3}	\$241.8/ton (Badger et al 2011)
VE_{k_4}	\$40/ton (Kim, Lee, Realff 20111)
VE_{k_5}	\$20/ton (Kim, Lee, Realff 20111)
YP_{k_3}	80% (Kim, Lee, Realff 20111)
YP_{k_4}	10% (Kim, Lee, Realff 20111)
YP_{k_5}	10% (Kim, Lee, Realff 20111)

Table 4-8 Material Balances Mobile

	Producing Task		**Consuming Tasks**		Incoming Transfer Task		Outgoing Transfer Task	
k	$\boldsymbol{P_k}$		$\overline{\boldsymbol{P_k}}$		T_k		$\overline{T_k}$	
k_1	$B_{ip_1t-120c}$	$\forall i,t,c$	B_{ip_1t-1c}	$\forall i,t,c$				
k_2	B_{ip_2t-1c}	$\forall i,t,c$	$B_{ip_{3-}p_6tc}$	$\forall i,t,c$				
k_3	$B_{ip_{3-}p_6t-1c}$	$\forall i,t,c$			$M_{i'ik_3tc}$	$\forall i', i\epsilon(L\cup F)$, $i'\epsilon, c$	$M_{ii'k_3tc}$	$\forall i, i'\epsilon(L$ $\cup F)$, $i\epsilon R, t, c$
k_4	$B_{ip_{3-}p_6t-1c}$	$\forall i,t,c$						
k_5	$B_{ip_{3-}p_6t-1c}$	$\forall i,t,c$						
$\overline{k_6}$	N_{ip_7tc}	$\forall i,t,c$	N_{ip_3tc}	$\forall i,t,c$	$N_{i'ik_6tc}$	$\forall i', i, t, c$		
$\overline{\overline{k_6}}$	N_{ip_3t-1c} N_{ip_5t-1c}	$\forall i,t,c$	N_{ip_7tc} N_{ip_5tc}	$\forall i,t,c$			$N_{ii'k_6tc}$	$\forall i, i', t, c$
$\overline{k_7}$	N_{ip_8tc}	$\forall i,t,c$	N_{ip_4tc}	$\forall i,t,c$	$N_{i'ik_7tc}$	$\forall i', i, t, c$		
$\overline{\overline{k_7}}$	N_{ip_4t-1c} N_{ip_6t-1c}	$\forall i,t,c$	N_{ip_8tc} N_{ip_6t}	$\forall i,t,c$			$N_{ii'k_7tc}$	$\forall i, i', t, c$

Table 4-9 Material Balance Fixed Processing Model

	Producing Task		**Consuming Tasks**		Incoming Transfer Task		Outgoing Transfer Task	
k	$\boldsymbol{P_k}$		$\overline{\boldsymbol{P_k}}$		T_k		$\overline{T_k}$	
k_1	$B_{ip_1t-120c}$	$\forall i,t,c$	B_{ip_1t-1c}	$\forall i,t,c$				
k_2	B_{ip_2t-1c}	$\forall i,t,c$	$B_{ip_{9-}p_{12}tc}$	$\forall i,t,c$	$T_{i'ik_2tc}$	$\forall i', i, t, c$	$T_{ii'k_2tc}$	$\forall i, i', t, c$
k_3	$B_{ip_{9-}p_{12}t-1c}$	$\forall i,t,c$			$T_{i'ik_3tc}$	$\forall i', i\epsilon(L\cup F)$, $i'\epsilon R, t, c$	$T_{ii'k_3tc}$	$\forall i, i'\epsilon(L\cup F)$, $i\epsilon R, t, c$

Biomass Material Balance

The general material balances for stage one and stage two decisions are included in Equation 4-1 and Equation 4-2.

Equation 4-1

$$S_{ikt} = S_{ikt-1} \times (1 - L_k) + \sum_{p \in P_k} B_{ipt-\tau_p} \times \rho_{ikpt} - \sum_{p \in \overline{P_k}} B_{ipt} \times \rho_{ikpt} + \sum_{i'} M_{i'ikt-\tau_k} - \sum_{i'} M_{ii'kt} \ \forall i, k \in k_{1\ldots5}, t$$

$$S_{ikt}, B_{ipt}, T_{ii'kt} \geq 0 \ \forall i, k, p, t$$

Equation 4-2

$$S_{iktc} = S_{ikt-1c} \times (1 - L_k) + \sum_{p \in P_k} B_{ipt-\tau_p \boldsymbol{c}} \times \rho_{ikpt} - \sum_{p \in \overline{P_k}} B_{ipt} \times \rho_{ikpt} + \sum_{i'} M_{i'ikt-\tau_k \boldsymbol{c}} - \sum_{i'} M_{ii'ktc} \ \forall i, k \in k_{1\ldots5}, t$$

$$S_{iktc}, B_{iptc}, T_{ii'ktc} \geq 0 \ \forall i, k, p, t, c$$

Planted Switchgrass

Notice that the switchgrass material balance in Equation 4-3 is not indexed by scenario, *c*. This is because switchgrass planting is considered a first stage, deterministic decision for the case study presented here.

Equation 4-3

$$S_{ik_1t} = S_{ik_1t-1} + B_{ip_1t-12} - B_{ip_1t-120} \ \forall i, t$$

$$S_{ik_1t} \leq MAX_{k_1} \ \forall \ i, t$$

Switchgrass growth dynamics are as outlined in Chapter II.

Harvested Biomass Storage

In the multi-period problem, harvested biomass storage decisions are considered second stage decisions. Storage decisions for mobile and centralized processing are outlined in Equation 4-4 and Equation 4-5 respectively.

Equation 4-4

$$S_{ik_2tc} = S_{ik_2t-1c} \times \left(1 - SL_{k_2}\right) + B_{ip_2t-1c} \times \rho_{ip_2k_2t} - \sum_{P \in p_3 \ldots p_6} B_{iptc} \ \forall i, t, c$$

Equation 4-5

$$\mathrm{S_{ik_2tc} = S_{ik_2t-1c} \times \left(1 - L_{k_2}\right) + B_{ip_2t-1c} \times \rho_{ik_2p_2t} - \sum_{p \in p_{9\ldots12}} B_{iptc} + \sum_{i'} M_{i'ik_2t-1c}} \ \ \forall \mathrm{i, t, c}$$

Balance on Oil Produced

For the mobile processing case, Equation 4-6 and Equation 4-7 include the material balances on oil produced for pipeline accessible, and non-pipeline accessible processing locations respectively. For the centralized processing case, Equation 4-8 and Equation 4-9 include material balances on oil produced for pipeline and none pipeline accessible processing locations. Finally, the balance for pyrolysis byproducts for mobile and fixed processing are included in Equation 4-10 and Equation 4-11 respectively.

Equation 4-6

$$\mathrm{S_{ik_3tc} = S_{ik_3t-1c} + \sum_{P \in p_{3\ldots6}} B_{ipt-1c} \times \rho_{ipk_3t}} + \sum\nolimits_{\mathrm{i'} \in \boldsymbol{R}} \mathrm{M_{i'ik_3tc}} - \sum_{\boldsymbol{f}} \mathrm{M_{ifk_3tc}} \ \ \forall \mathrm{i} \in \boldsymbol{L}, \mathrm{t, c}$$

Equation 4-7

$$\mathrm{S_{ik_3tc} = S_{ik_3t-1c} + \sum_{P \in p_{3\ldots6}} B_{ipt-1c} \times \rho_{ipk_3t}} - \sum_{\mathrm{i'} \in \boldsymbol{L}} \mathrm{M_{ii'^{k_3}tc}} \ \ \forall \mathrm{i} \in \boldsymbol{R}, \mathrm{t, c}$$

Equation 4-8

$$\mathrm{S_{ik_3tc} = S_{ik_3t-1c} + \sum_{p \epsilon p_{9\ldots}p_{12}} B_{i\boldsymbol{p}t-1c} \times \rho_{i\boldsymbol{p}k_3t}} + \sum\nolimits_{\mathrm{i'} \in \boldsymbol{R}} \mathrm{M_{i'ik_3tc}} - \sum\nolimits_{\mathrm{f}} \mathrm{M_{ifktc}} \ \ \forall \mathrm{i} \in \boldsymbol{L}, \mathrm{t, c}$$

Equation 4-9

$$\mathrm{S_{ik_3tc} = S_{ik_3t-1c} + B_{ip_{9\ldots12}t-1c} \times \rho_{i\boldsymbol{p}k_3t}} - \sum_{\mathrm{i'} \in \boldsymbol{L}} \mathrm{T_{ii'^{k_3}tc}} \ \ \forall \mathrm{i} \in \boldsymbol{R}, \mathrm{t, c}$$

Equation 4-10

$$\mathrm{S_{iktc} = S_{ikt-1c} + \sum_{p \in p_{3\ldots6}} B_{ipt-1c} \times \rho_{ipkt}} \ \ \forall \mathrm{i, k} \in k_{4\ldots5}. \mathrm{t, c}$$

Equation 4-11

$$\mathrm{S_{ikt} = S_{ikt-1c} + \sum_{p \in p_{9\ldots12}} B_{ipt-1}c \times \rho_{ipkt}} \ \ \forall \mathrm{i, k} \in k_{4\ldots5}. \mathrm{t, c}$$

Biomass Processing Capacity Constraints

The biomass processing tasks in the mobile case is limited by the availability of mobile units at a particular harvest location as shown in **Equation 4-12**.

Equation 4-12

$$\mathbf{B_{iptc} \leq N_{iptc} \times Max_{p} \forall i, p, t, c}$$

The number of mobile units is a second stage decision in the multi period planning as it is assumed that mobile processing capacity can be adjusted on an annual basis in response to varying crop yields. The material balances on mobile units are equivalent to that of chapter II, with the exception of the addition of an additional index c to designate different scenarios.

Equation 4-13

$$\mathrm{N}_{\mathrm{i}\overline{\mathrm{k}_6}\mathrm{tc}} = \mathrm{N}_{\mathrm{i}\overline{\mathrm{k}_6}\mathrm{t-1c}} + \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{i}'\mathrm{ik}_6\,\mathrm{t-1c}} + \mathrm{N}_{\mathrm{ip}_7\,\mathrm{tc}} - \mathrm{N}_{\mathrm{ip}_3\,\mathrm{tc}}\ \forall \mathrm{i}, \mathrm{t}, \mathrm{c}$$

Equation 4-14

$$\mathrm{N}_{\mathrm{i}\overline{\mathrm{k}_7}\mathrm{tc}} = \mathrm{N}_{\mathrm{i}\overline{\mathrm{k}_7}\mathrm{t-1c}} + \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{i}'\mathrm{ik}_7\,\mathrm{t-1c}} + \mathrm{N}_{\mathrm{ip}_8\,\mathrm{tc}} - \mathrm{N}_{\mathrm{ip}_4\,\mathrm{tc}}\ \forall \mathrm{i}, \mathrm{t}, \mathrm{c}$$

Equation 4-15

$$\mathrm{N}_{\mathrm{i}\overline{\overline{k_6}}\mathrm{tc}} = \mathrm{N}_{\mathrm{i}\overline{\overline{k_6}}\mathrm{t-1c}} + \mathrm{N}_{\mathrm{ip}_5\,\mathrm{t-1c}} - \mathrm{N}_{\mathrm{ip}_5\,\mathrm{tc}} - \mathrm{N}_{\mathrm{ip}_7\,\mathrm{tc}} - \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{ii}'_{k_6}\,\mathrm{tc}}\ \ \forall \mathrm{i}, \mathrm{t}$$

Equation 4-16

$$\mathbf{N}_{\mathbf{i}\overline{\overline{\boldsymbol{k}_7}}\mathbf{tc}} = \mathbf{N}_{\mathbf{i}\overline{\overline{\boldsymbol{k}_7}}\mathbf{t-1c}} + \mathbf{N}_{\mathbf{ip}_6\,\mathbf{t-1c}} - \mathbf{N}_{\mathbf{ip}_6\,\mathbf{tc}} - \mathbf{N}_{\mathbf{ip}_8\,\mathbf{tc}} - \sum_{\mathbf{i}'} \mathbf{N}_{\mathbf{ii}'_{\boldsymbol{k}_7}\,\mathbf{t}}\boldsymbol{c}\ \ \forall \mathbf{i}, \mathbf{t}, \mathbf{c}$$

Equation 4-17

$$\mathrm{N}_{\mathrm{i}\overline{\overline{k}}\,\mathrm{t}} \leq Max_k\ \ , Max_k = 0, k \in k_{6\cdots7}$$

Equation 4-18

$$\mathrm{N}_{\mathrm{iktc}} \geq 0$$

The equipment purchase decision for each scenario are shown in Equation 4-19

Equation 4-19

$$\sum_{\mathrm{i}} \mathrm{N}_{\mathrm{ikt}_0} + \sum_{\mathrm{i}} \sum_{\mathrm{i}'} \mathrm{N}_{\mathrm{ii}'\mathrm{k}\,\mathrm{t}_0} + \sum_{\mathrm{i}} \sum_{\mathrm{p} \in \overline{\mathrm{P}_\mathrm{k}}} \mathrm{N}_{\mathrm{ipt}_0}\ = \mathrm{N}_\mathrm{k}^\mathrm{T}\ \forall\ \mathrm{k} \in \mathrm{k}_{6\ldots7}$$

Unlike the mobile case, centralized processing involves permanent refinery capacity. The quantity of biomass that can be processed in any particular time period is less than the maximum quantity of biomass corresponding to the choice of capacity at candidate refineries. This is described in Equation 4-20.

Equation 4-20

$$B_{i\boldsymbol{p}tc} \leq \mathrm{Max}_{p} \times W_{i\boldsymbol{p}} \ \forall \ ip \in p_{9\ldots12}, t, c$$

Note that W_{ip} is not indexed by scenario *c;* this is because biomass processing capacity is considered a first stage decision in this case study. Also, at most one refinery can be selected at each location.

Equation 4-21

$$\sum\nolimits_{\boldsymbol{p} \in p_{9\ldots12}} W_{ip} \ \leq 1 \forall \ i, t$$

Balance on Oil at Final Refining Location and Objective Function

The quantity of oil at the final processing location is expressed in Equation 4-22.

Equation 4-22

$$S_{fk_3tc} = S_{fk_3t-1c} + \sum\nolimits_{\boldsymbol{i} \in \boldsymbol{L}} M_{\boldsymbol{i}fk_3tc} \ \forall f, t, c$$

The optimization model presented here employs an economic objective function that maximizes the NPV of first stage decisions and the expected value of second stage activities. The objective functions for the mobile processing and centralized processing case are shown in Equation 4-23 and Equation 4-24 respectively.

Equation 4-23

Maximize

$$\mathrm{NPV} = \sum\nolimits_{\boldsymbol{c}} \in_{\boldsymbol{c}} \times \Big[S_{fk_3t_{14}\boldsymbol{c}} \times VE_{k_3} + \sum\nolimits_{t} \sum\nolimits_{i} \sum\nolimits_{p \in p_{3-6}} V_{ip} \times B_{iptc} - \sum\nolimits_{t} \sum\nolimits_{i} \big(+B_{ip_2tc} \times CV_{p_2}\big) \times \beta_i - \sum\nolimits_{t} \sum\nolimits_{k \in k_3} \sum\nolimits_{i} \sum\nolimits_{i'} M_{ii'k\,tc} \times CV_{ii'k} - \sum\nolimits_{t} \sum\nolimits_{k \in k_{6\ldots7}} \sum\nolimits_{i} \sum\nolimits_{i'} N_{ii'k\,tc} \times CV_{ii'k} - \sum\nolimits_{k \in k_{6\ldots7}} N^{T}{}_{kc} \times CF_k\Big] - \sum\nolimits_{\boldsymbol{t}} \sum\nolimits_{\boldsymbol{i}} B_{ip_1t} \times CV_{p_1} \times \beta_i$$

Equation 4-24

Maximize

$$\begin{aligned}\mathrm{NPV} = \sum_{c} \in_{c} \times \Bigg[& \mathrm{S}_{\mathrm{fk_3 t_{14}}c} \times \mathrm{VE}_{\mathrm{k_3}} + \sum_{\mathrm{t}} \sum_{\mathrm{i}} \sum_{\mathrm{p \in p_{9-16}}} \mathrm{V}_{\mathrm{ip}} \times \mathrm{B}_{\mathrm{iptc}} \\ & - \sum_{\mathrm{t}} \sum_{\mathrm{i}} \left(\mathrm{B}_{\mathrm{ip_2 tc}} \times \mathrm{CV}_{\mathrm{p_2}} \right) \times \beta_{\mathrm{i}} - \sum_{\mathrm{t}} \sum_{\mathrm{K \in k_2 \cup k_{8 \ldots 11}}} \sum_{\mathrm{i}} \sum_{\mathrm{i'}} \mathrm{M}_{\mathrm{ii'k\,tc}} \times \mathrm{CV}_{\mathrm{ii'k}} \Bigg] \\ & - \sum_{\mathrm{i}} \sum_{\mathrm{P \in p_{9 \ldots 12}}} \mathrm{W}_{\mathrm{ip}} \times \mathrm{CF}_{\mathrm{k}} - \sum_{t} \sum_{i} \mathrm{B}_{\mathrm{ip_1 t}} \times \mathrm{CV}_{\mathrm{p_1}} \times \beta_{\mathrm{i}} \end{aligned}$$

Multi-Period Planning Problem Results

For both current and future climate scenarios, the mobile and centralized processing models are solved for cases in which ten percent of available cropland can be planted. Results for 5 year planning periods for both current and future climate scnearos (2008-2012 and 2048-2052) are outlined in Table 4-10 and Table 4-11 respectively.

Table 4-10 2008-2012 Multi Period Optimization Model Results

	2008		2009		2010		2011		2012	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	9.78E+06	9.47E+06	9.78E+06	9.47E+06	9.78E+06	9.47E+06	9.78E+06	9.47E+06	9.78E+06	9.47E+06
Tons of Biomass Processed	7.12E+07	9.67E+07	6.78E+07	9.20E+07	6.93E+07	9.38E+07	6.99E+07	9.51E+07	6.21E+07	8.53E+07
Planting and Harvesting Costs	3.15E+09	3.05E+09	3.15E+09	3.05E+09	3.15E+09	3.05E+09	3.15E+09	3.05E+09	3.15E+09	3.05E+09
Variable Processing Costs	6.13E+08	8.32E+08	5.84E+08	7.92E+08	5.97E+08	8.08E+08	6.02E+08	8.19E+08	5.35E+08	7.35E+08
Fixed Processing Costs	3.57E+09	1.51E+09	3.42E+09	1.51E+09	3.51E+09	1.51E+09	3.52E+09	1.51E+09	3.18E+09	1.51E+09
--	1.73E+06	--	1.70E+06	--	1.72E+06	--	1.70E+06	--	1.62E+06	--
Mobile Unit Transportation Cost/Centralized Harvested Biomass Transportation Cost	1.12E+05	1.48E+09	1.14E+05	1.42E+09	1.13E+05	1.46E+09	1.10E+05	1.45E+09	1.15E+05	1.27E+09
Cost Oil Transport Truck	1.05E+09	9.90E+08	1.01E+09	9.45E+08	1.05E+09	9.83E+08	1.04E+09	9.91E+08	9.29E+08	8.88E+08
Cost Oil Transport Pipeline	6.05E+08	6.26E+08	5.76E+08	5.95E+08	5.96E+08	6.18E+08	5.93E+08	6.17E+08	5.26E+08	5.51E+08
Oil and Byproduct Value	1.42E+10	1.47E+10	1.35E+10	1.40E+10	1.38E+10	1.43E+10	1.39E+10	1.45E+10	1.24E+10	1.30E+10
Annual Profit	5.24E+09	6.21E+09	4.77E+09	5.67E+09	4.91E+09	5.91E+09	5.01E+09	6.07E+09	4.05E+09	4.99E+09
Overal NPV	4.80E+09	5.77E+09								
NPV Deterministic	5.42E+09	7.03E+09	4.98E+09	6.60E+09	5.18E+09	6.78E+09	5.27E+09	6.82E+09	4.44E+09	5.77E+09
Annual Profit/NPV Deterministic	97%	88%	96%	86%	95%	87%	95%	89%	91%	86%

Table 4-11 2048-2052 Multi Period Optimization Model Results

	2048		2049		2050		2051		2052	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	8.42E+06	8.52E+06	8.42E+06	8.52E+06	8.42E+06	8.52E+06	8.42E+06	8.52E+06	8.42E+06	8.52E+06
Tons of Biomass Processed	5.87E+07	8.31E+07	5.78E+07	8.25E+07	5.82E+07	8.28E+07	5.83E+07	8.29E+07	5.82E+07	8.25E+07
Planting and Harvesting Costs	2.71E+09	2.74E+09	2.71E+09	2.74E+09	2.71E+09	2.74E+09	2.71E+09	2.74E+09	2.71E+09	2.74E+09
Variable Processing Costs	5.05E+08	7.16E+08	4.98E+08	7.10E+08	5.01E+08	7.13E+08	5.02E+08	7.14E+08	5.01E+08	7.10E+08
Fixed Processing Costs	2.97E+09	1.04E+09	2.91E+09	1.04E+09	2.94E+09	1.04E+09	2.95E+09	1.04E+09	2.94E+09	1.04E+09
Mobile Unit Setup Cost	1.43E+06	--	1.45E+06	--	1.43E+06	--	1.44E+06	--	1.46E+06	--
Mobile Unit Transportation Cost/Centralized Harvested Biomass Transportation Cost	9.36E+04	1.19E+09	1.01E+05	1.19E+09	9.52E+04	1.19E+09	9.47E+04	1.18E+09	1.02E+05	1.18E+09
Cost Oil Transport Truck	9.42E+08	9.02E+08	9.27E+08	8.94E+08	9.29E+08	8.93E+08	9.24E+08	8.85E+08	9.34E+08	8.99E+08
Cost Oil Transport Pipeline	5.22E+08	5.46E+08	5.15E+08	5.42E+08	5.16E+08	5.42E+08	5.15E+08	5.40E+08	5.18E+08	5.43E+08
Oil and Byproduct Value	1.17E+10	1.23E+10	1.15E+10	1.22E+10	1.16E+10	1.22E+10	1.16E+10	1.22E+10	1.16E+10	1.22E+10
Annual Profit	4.00E+09	5.14E+09	3.99E+09	5.07E+09	4.05E+09	5.11E+09	4.05E+09	5.12E+09	4.04E+09	5.08E+09
Overall NPV	4.03E+09	5.10E+09								
NPV Deterministic	4.18E+09	5.50E+09	4.14E+09	5.48E+09	4.10E+09	5.52E+09	4.13E+09	5.52E+09	4.17E+09	5.44E+09
Annual Profit/NPV Deterministic	96%	93%	96%	93%	99%	93%	98%	93%	97%	93%

Recall that the NPV for both the mobile and fixed processing designs is defined as the NPV of first stage decisions plus the expected NPV of second stage decisions. First stage decisions for mobile processing include planting decisions only, while first stage decisions for centralized processing include planting decisions and the capacity and location of processing facilities. For comparison, Table 4-10 and Table 4-11 also include values for single stage deterministic NPV for each of the described scenarios. Naturally, the single stage deterministic NPV values are higher than that of the stochastic multi-period solutions. Also notice that the future climate scenario solutions have smaller NPVs than that of current climate scenarios.

One interesting metric to consider is the ratio of NPV stochastic to NPV deterministic for each year in the 5-year planning period. This ratio is indicative of how much the solution degrades in the presence of uncertainty. For both the current and future climate scenarios, this ratio is higher for the mobile processing design than the centralized processing design. Thus, the mobile processing design appears to be more robust to uncertainty in switchgrass yields. Although the NPV for centralized processing is still higher than that of the mobile processing design, the gap between the NPV centralized and NPV mobile is less in the stochastic scenarios as compared to the deterministic case.

Another experiment of interest is fixing the first stage decisions according to the design derived from a particular climate scenario, and obtaining a model solution for the alternate climate scenario. For example, the planting (mobile and centralized) and capacity (centralized) decisions determined by the multi period 2008-2012 models are applied to the 2048-2012 switchgrass yield scenario. That is the objective function is the sum of NPV of the first stage decisions determined by the 2008-2012 model and the expected value of the second stage decisions under the 2048-2052-climate scenario. In addition, Equation 4-3 is altered for both the mobile and centralized cases in order to constrain switchgrass planting at each location to the value determined according to the 2008-2012 model. For the centralized case, Equation 4-20 is also altered to limit processing capacity at each location to the value determined by the 2008-2012 model. The results for the experiment in which first stage decisions are fixed according to alternate climate scenarios are included in Table 4-12 and Table 4-13 respectively. Specifically, Table 4-12 demonstrates the 2008-2012 solution fixed according to 2048-2052 first stage decisions, while Table 4-13 demonstrates the 2048-2052 solution fixed according to 2008-2012 first stage decisions.

Table 4-12 2008-2012 Results fixed According to 2048-2052 First Stage Decisions

	2008		2009		2010		2011		2012	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	8.42E+06	9.47E+06	8.42E+06	9.47E+06	8.42E+06	9.47E+06	8.42E+06	9.47E+06	8.42E+06	9.47E+06
Tons of Biomass Processed	6.03E+07	7.48E+07	5.71E+07	7.27E+07	5.91E+07	7.48E+07	5.99E+07	7.44E+07	5.46E+07	6.88E+07
Planting and Harvesting Costs	2.71E+09	3.05E+09	2.71E+09	3.05E+09	2.71E+09	3.05E+09	2.71E+09	3.05E+09	2.71E+09	3.05E+09
Variable Processing Costs	5.19E+08	6.44E+08	4.92E+08	6.26E+08	5.09E+08	6.44E+08	5.15E+08	6.40E+08	4.70E+08	5.92E+08
Fixed Processing Costs	3.07E+09	--	2.95E+09	--	3.06E+09	--	3.09E+09	--	2.85E+09	--
Mobile Unit Transportation Cost/Centralized Harvested Biomass Transportation Cost	1.16E+06	7.07E+08	1.11E+06	7.07E+08	1.14E+06	7.07E+08	1.13E+06	7.07E+08	1.06E+06	7.07E+08
Mobile Unit Transportation Cost	3.08E+04	1.28E+09	2.86E+04	1.29E+09	2.65E+04	1.28E+09	2.19E+04	1.27E+09	2.68E+04	1.22E+09
Cost Oil Transport Truck	8.98E+08	2.37E+09	8.58E+08	2.37E+09	8.98E+08	2.37E+09	9.07E+08	2.37E+09	8.22E+08	2.37E+09
Cost Oil Transport Pipeline	5.23E+08	7.74E+08	4.96E+08	7.53E+08	5.19E+08	7.94E+08	5.18E+08	7.81E+08	4.68E+08	7.08E+08
Oil and Byproduct Value	1.20E+10	1.03E+10	1.14E+10	1.00E+10	1.18E+10	1.03E+10	1.19E+10	1.03E+10	1.09E+10	9.44E+09
Annual Profit	4.31E+09	4.88E+09	3.89E+09	4.58E+09	4.09E+09	4.87E+09	4.20E+09	4.83E+09	3.57E+09	4.16E+09
Overall NPV	4.01E+09	4.66E+09								
NPV Deterministic	5.42E+09	7.03E+09	4.98E+09	6.60E+09	5.18E+09	6.78E+09	5.27E+09	6.82E+09	4.44E+09	5.77E+09
Annual Profit/NPV Deterministic	79%	69%	78%	69%	79%	72%	80%	71%	80%	72%

Table 4-13 2048-2052 Results Fixed According to 2008-2012 First Stage Decision

	2048		2049		2050		2051		2052	
	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central	Mobile	Central
Acres of Switchgrass Planted	9.78E+06	7.51E+06	9.78E+06	7.51E+06	9.78E+06	7.51E+06	9.78E+06	7.51E+06	9.78E+06	7.51E+06
Tons of Biomass Processed	5.89E+07	6.61E+07	5.90E+07	6.57E+07	5.92E+07	6.58E+07	5.93E+07	6.58E+07	5.84E+07	6.56E+07
Planting and Harvesting Costs	3.15E+09	2.42E+09	3.15E+09	2.42E+09	3.15E+09	2.42E+09	3.15E+09	2.42E+09	3.15E+09	2.42E+09
Variable Processing Costs	5.07E+08	5.69E+08	5.08E+08	5.66E+08	5.10E+08	5.67E+08	5.10E+08	5.66E+08	5.03E+08	5.65E+08
Fixed Processing Costs	3.19E+09	1.34E+09	3.25E+09	1.34E+09	3.25E+09	1.34E+09	3.24E+09	1.34E+09	3.19E+09	1.34E+09
Mobile Unit Setup Cost	1.23E+06	--	1.24E+06	--	1.26E+06	--	1.24E+06	--	1.23E+06	--
Mobile Unit Transportation Cost/Centralized Harvested Biomass Transportation Cost	3.56E+04	9.29E+08	3.38E+04	9.27E+08	3.83E+04	9.21E+08	3.50E+04	9.17E+08	3.45E+04	9.19E+08
Cost Oil Transport Truck	9.28E+08	7.87E+08	9.26E+08	7.83E+08	9.28E+08	7.80E+08	9.19E+08	7.72E+08	9.19E+08	7.83E+08
Cost Oil Transport Pipeline	5.21E+08	5.10E+08	5.21E+08	5.07E+08	5.21E+08	5.06E+08	5.19E+08	5.04E+08	5.17E+08	5.07E+08
Oil and Byproduct Value	1.17E+10	1.05E+10	1.18E+10	1.05E+10	1.18E+10	1.05E+10	1.18E+10	1.05E+10	1.16E+10	1.04E+10
Annual Profit	3.45E+09	3.96E+09	3.42E+09	3.92E+09	3.46E+09	3.93E+09	3.48E+09	5.12E+09	3.36E+09	3.91E+09
Overall NPV	3.43E+09	4.17E+09								
NPV Deterministic	4.18E+09	5.50E+09	4.14E+09	5.48E+09	4.10E+09	5.52E+09	4.13E+09	5.52E+09	4.17E+09	5.44E+09
Annual Profit/NPV Deterministic	83%	72%	82%	72%	84%	71%	84%	93%	81%	72%

Naturally, the ratio of NPV stochastic to NPV deterministic for the cases in which the first stage decisions are fixed according to the model results for an alternate climate scenarios is smaller than the case in which first stage decisions are not fixed according to model results for a different climate scenario. As in the previous stochastic case, this ratio is higher for the mobile processing case than it is for the fixed processing case, further confirming the assertion that the mobile processing design is more robust to uncertainty in crop yield design. Additionally, for the solutions included in Table 4-12 and Table 4-13, the gap in NPV between mobile and centralized processing is even smaller than in previous solutions. Thus, as more uncertainty and supply chain shocks are introduced, the performance of the mobile processing design relative to the centralize design seems to improve. Also, notice that the NPV values are slightly higher for the case in which first stage decisions are fixed according to the future climate scenario in which switchgrass yields are lower. This suggests that in biorefinery network planning, a policy of considering the worst-case scenario for crop yield could be advantageous.

Recall that the typical stand-life for switchgrass is 10 years. However, the planning period lengths that have been considered thus far for the two-stage stochastic problem are only 5 years. A more realistic scenario would be to model a two-stage optimization model in which first stage decisions are fixed at the beginning of a 10-year planning horizon. As in the previous cases, first stage decisions for both mobile and centralized processing include planting decisions, while both planting and processing decisions are fixed for the centralized design. Three 10-year planning periods for current climate scnearios are modeled in this chapter. The planning periods include projected switchgrass yields for the years 1979-1988, 1989-1998, and 1999-2008. These solutions are included in Table 4-14, Table 4-15, and Table 4-16 respectively. Notice that when considering a 10-year planning horizon, (arguably, the most realistic scenario as the typical life of switchgrass stand is 10 years), the mobile processing design performs better than the centralized processing design.

Table 4-14 Multi Period Planning Problem with 10 year Planning Horizon (1979-1988)

Mobile	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Acres of Switchgrass Planted	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06
Tons of Biomass Processed	6.89E+07	6.93E+07	6.38E+07	6.43E+07	6.83E+07	6.88E+07	6.72E+07	6.18E+07	6.13E+07	7.11E+07
Planting and Harvesting Costs	3.16E+09	3.16E+09	3.16E+09	3.16E+09	3.16E+09	3.16E+09	3.16E+09	3.16E+09	3.16E+09	3.16E+09
Variable Processing Costs	5.93E+08	5.97E+08	5.49E+08	5.54E+08	5.88E+08	5.92E+08	5.79E+08	5.32E+08	5.28E+08	6.12E+08
Fixed Processing Costs	3.42E+09	3.47E+09	3.22E+09	3.22E+09	3.41E+09	3.44E+09	3.35E+09	3.14E+09	3.10E+09	3.53E+09
Mobile Unit Setup Cost	1.77E+06	1.81E+06	1.66E+06	1.69E+06	1.74E+06	1.78E+06	1.72E+06	1.68E+06	1.68E+06	1.81E+06
Mobile Unit Transportation Cost	1.17E+05	1.20E+05	1.04E+05	1.14E+05	1.08E+05	1.16E+05	1.11E+05	1.14E+05	1.15E+05	1.14E+05
Cost Oil Transport Truck	1.03E+09	1.03E+09	9.62E+08	9.55E+08	1.03E+09	1.02E+09	9.97E+08	9.17E+08	9.32E+08	1.05E+09
Cost Oil Transport Pipeline	5.89E+08	5.88E+08	5.42E+08	5.50E+08	5.88E+08	5.85E+08	5.73E+08	5.22E+08	5.30E+08	5.97E+08
Oil and Byproduct Value	1.37E+10	1.38E+10	1.27E+10	1.28E+10	1.36E+10	1.37E+10	1.34E+10	1.23E+10	1.23E+10	1.42E+10
Annual Profit	4.92E+09	4.97E+09	4.25E+09	4.35E+09	4.83E+09	4.91E+09	4.74E+09	4.00E+09	4.02E+09	5.28E+09
NPV	4.63E+09									
Centralized	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Acres of Switchgrass Planted	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06
Tons of Biomass Processed	5.36E+07	5.36E+07	4.95E+07	5.00E+07	5.32E+07	5.42E+07	5.28E+07	4.82E+07	4.82E+07	5.62E+07
Planting and Harvesting Costs	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09	1.90E+09
Variable Processing Costs	4.61E+08	4.62E+08	4.27E+08	4.30E+08	4.58E+08	4.67E+08	4.54E+08	4.15E+08	4.15E+08	4.84E+08
Fixed Processing Costs	6.11E+08	6.11E+08	6.11E+08	6.11E+08	6.11E+08	6.11E+08	6.11E+08	6.11E+08	6.11E+08	6.11E+08
Centralized Harvested Biomass Transportation Cost	9.56E+08	9.49E+08	8.84E+08	8.77E+08	9.49E+08	9.62E+08	9.35E+08	8.53E+08	8.63E+08	9.90E+08
Cost Oil Transport Truck	4.42E+08	4.34E+08	4.12E+08	4.05E+08	4.41E+08	4.45E+08	4.34E+08	3.90E+08	4.07E+08	4.60E+08
Cost Oil Transport Pipeline	3.63E+08	3.59E+08	3.33E+08	3.35E+08	3.60E+08	3.65E+08	3.55E+08	3.20E+08	3.28E+08	3.75E+08
Oil and Byproduct Value	8.47E+09	8.46E+09	7.82E+09	7.88E+09	8.41E+09	8.56E+09	8.33E+09	7.59E+09	7.63E+09	8.87E+09
Annual Profit	3.74E+09	2.79E+09	3.26E+09	3.33E+09	3.69E+09	3.81E+09	3.65E+09	3.11E+09	3.11E+09	4.05E+09
NPV	3.46E+09									

Table 4-15 Multi Period Planning Problem with 10 year Planning Horizon (1989-1998)

Mobile	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Acres of Switchgrass Planted	9.53E+06	9.53E+06	9.53E+06	9.53E+06	9.53E+06	9.53E+06	9.53E+06	9.53E+06	9.53E+06	9.53E+06
Tons of Biomass Processed	6.40E+07	6.53E+07	5.73E+07	6.72E+07	6.69E+07	6.46E+07	6.74E+07	6.53E+07	6.85E+07	6.90E+07
Planting and Harvesting Costs	3.07E+09	3.07E+09	3.07E+09	3.07E+09	3.07E+09	3.07E+09	3.07E+09	3.07E+09	3.07E+09	3.07E+09
Variable Processing Costs	5.51E+08	5.62E+08	4.93E+08	5.79E+08	5.76E+08	5.56E+08	5.80E+08	5.62E+08	5.90E+08	5.94E+08
Fixed Processing Costs	3.21E+09	3.29E+09	2.92E+09	3.36E+09	3.36E+09	3.27E+09	3.38E+09	3.25E+09	3.41E+09	3.43E+09
Mobile Unit Setup Cost	1.54E+06	1.58E+06	1.44E+06	1.58E+06	1.57E+06	1.56E+06	1.60E+06	1.53E+06	1.61E+06	1.66E+06
Mobile Unit Transportation Cost	8.94E+04	8.80E+04	8.91E+04	9.18E+04	8.78E+04	8.68E+04	8.88E+04	8.84E+04	9.15E+04	9.88E+04
Cost Oil Transport Truck	9.38E+08	9.55E+08	8.53E+08	9.90E+08	9.82E+08	9.54E+08	9.89E+08	9.68E+08	9.98E+08	1.01E+09
Cost Oil Transport Pipeline	5.48E+08	5.53E+08	4.95E+08	5.72E+08	5.72E+08	5.51E+08	5.73E+08	5.55E+08	5.87E+08	5.87E+08
Oil and Byproduct Value	1.28E+10	1.30E+10	1.14E+10	1.34E+10	1.33E+10	1.29E+10	1.34E+10	1.30E+10	1.37E+10	1.37E+10
Annual Profit	4.47E+09	4.56E+09	3.61E+09	4.83E+09	4.74E+09	4.49E+09	4.81E+09	4.59E+09	5.05E+09	5.02E+09
NPV	4.62E+09									
Centralized	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Acres of Switchgrass Planted	4.45E+06	4.45E+06	4.45E+06	4.45E+06	4.45E+06	4.45E+06	4.45E+06	4.45E+06	4.45E+06	4.45E+06
Tons of Biomass Processed	3.79E+07	3.60E+07	3.36E+07	4.10E+07	4.02E+07	3.75E+07	4.01E+07	4.00E+07	4.03E+07	4.09E+07
Planting and Harvesting Costs	1.43E+09	1.43E+09	1.43E+09	1.43E+09	1.43E+09	1.43E+09	1.43E+09	1.43E+09	1.43E+09	1.43E+09
Variable Processing Costs	3.26E+08	3.10E+08	2.89E+08	3.53E+08	3.46E+08	3.23E+08	3.45E+08	3.44E+08	3.47E+08	3.52E+08
Fixed Processing Costs	8.83E+08	8.83E+08	8.83E+08	8.83E+08	8.83E+08	8.83E+08	8.83E+08	8.83E+08	8.83E+08	8.83E+08
Centralized Harvested Biomass Transportation Cost	5.61E+08	5.19E+08	5.00E+08	6.20E+08	6.00E+08	5.56E+08	5.89E+08	6.07E+08	5.97E+08	6.08E+08
Cost Oil Transport Truck	3.56E+08	3.33E+08	3.17E+08	3.91E+08	3.78E+08	3.55E+08	3.75E+08	3.83E+08	3.77E+08	3.83E+08
Cost Oil Transport Pipeline	2.31E+08	2.10E+08	2.05E+08	2.49E+08	2.45E+08	2.24E+08	2.41E+08	2.42E+08	2.46E+08	2.47E+08
Oil and Byproduct Value	5.97E+09	5.67E+09	5.29E+09	6.47E+09	6.34E+09	5.91E+09	6.32E+09	6.30E+09	6.36E+09	6.44E+09
Annual Profit	2.18E+09	1.42E+09	1.67E+09	2.54E+09	2.45E+09	2.13E+09	2.45E+09	2.41E+09	2.47E+09	2.54E+09
NPV	2.22E+09									

Table 4-16 Multi Period Planning Problem with 10 year Planning Horizon (1999-2008)

Mobile	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Acres of Switchgrass Planted	9.47E+06	9.47E+06	9.47E+06	9.47E+06	9.47E+06	9.47E+06	9.47E+06	9.47E+06	9.47E+06	9.47E+06
Tons of Biomass Processed	6.36E+07	6.20E+07	6.56E+07	6.42E+07	6.67E+07	6.42E+07	7.03E+07	6.38E+07	6.72E+07	6.90E+07
Planting and Harvesting Costs	3.05E+09	3.05E+09	3.05E+09	3.05E+09	3.05E+09	3.05E+09	3.05E+09	3.05E+09	3.05E+09	3.05E+09
Variable Processing Costs	5.48E+08	5.34E+08	5.65E+08	5.53E+08	5.74E+08	5.53E+08	6.05E+08	5.49E+08	5.79E+08	5.94E+08
Fixed Processing Costs	3.22E+09	3.17E+09	3.32E+09	3.27E+09	3.38E+09	3.25E+09	3.53E+09	3.24E+09	3.40E+09	3.46E+09
Mobile Unit Setup Cost	1.47E+06	1.40E+06	1.51E+06	1.48E+06	1.50E+06	1.48E+06	1.59E+06	1.43E+06	1.52E+06	1.54E+06
Mobile Unit Transportation Cost	7.43E+04	6.60E+04	7.32E+04	7.52E+04	6.89E+04	7.59E+04	7.07E+04	6.18E+04	7.27E+04	7.43E+04
Cost Oil Transport Truck	9.34E+08	9.11E+08	9.65E+08	9.49E+08	9.87E+08	9.53E+08	1.03E+09	9.34E+08	1.00E+09	1.01E+09
Cost Oil Transport Pipeline	5.45E+08	5.26E+08	5.65E+08	5.52E+08	5.72E+08	5.54E+08	6.02E+08	5.40E+08	5.76E+08	5.90E+08
Oil and Byproduct Value	1.27E+10	1.24E+10	1.31E+10	1.28E+10	1.33E+10	1.28E+10	1.40E+10	1.27E+10	1.34E+10	1.37E+10
Annual Profit	4.38E+09	4.18E+09	4.63E+09	4.41E+09	4.74E+09	4.42E+09	5.20E+09	4.37E+09	4.80E+09	5.01E+09
NPV	4.61E+09									
Centralized	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Acres of Switchgrass Planted	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06
Tons of Biomass Processed	2.84E+07	2.72E+07	3.04E+07	3.04E+07	3.21E+07	2.99E+07	3.25E+07	2.83E+07	3.20E+07	3.19E+07
Planting and Harvesting Costs	1.12E+09	1.12E+09	1.12E+09	1.12E+09	1.12E+09	1.12E+09	1.12E+09	1.12E+09	1.12E+09	1.12E+09
Variable Processing Costs	2.45E+08	2.34E+08	2.62E+08	2.62E+08	2.76E+08	2.58E+08	2.80E+08	2.44E+08	2.75E+08	2.74E+08
Fixed Processing Costs	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08
--	--	--	--	--	--	--	--	--	--	--
Mobile Unit Transportation Cost	4.78E+08	4.54E+08	5.28E+08	5.21E+08	5.55E+08	5.22E+08	5.63E+08	4.79E+08	5.45E+08	5.47E+08
Cost Oil Transport Truck	2.33E+08	2.28E+08	2.56E+08	2.58E+08	2.79E+08	2.54E+08	2.75E+08	2.35E+08	2.79E+08	2.67E+08
Cost Oil Transport Pipeline	2.16E+08	2.06E+08	2.34E+08	2.33E+08	2.47E+08	2.30E+08	2.50E+08	2.14E+08	2.45E+08	2.43E+08
Oil and Byproduct Value	4.35E+09	4.17E+09	4.68E+09	4.67E+09	4.95E+09	4.61E+09	5.00E+09	4.33E+09	4.91E+09	4.89E+09
Annual Profit	1.57E+09	9.50E+08	1.78E+09	1.78E+09	1.97E+09	1.73E+09	2.02E+09	1.54E+09	1.95E+09	1.95E+09
NPV	1.72E+09									

Multi Period Planning Problem Discussion and Recommendations

It has been demonstrated that biorefinery networks for both mobile and fixed processing designs can be modeled for large geographic areas in the presence of uncertainty in feedstock supply. For the stationary processing in particular, by and large, the models seemed to select smaller more distributed facilities. When comparing the mobile processing design to the centralized processing design, the NPV of centralized processing designs is slightly better than that of the mobile processing design for deterministic cases. However, as uncertainty is introduced the mobile processing solution does not degrade as quickly as that of the centralized solution. In fact, when considering a two-stage stochastic model over a 10 year planning horizon, the mobile processing design is more profitable than the centralized processing design. Since the typical stand life of switchgrass is 10 years, one could argue that the two-stage stochastic model with a 10-year project life is perhaps the most realistic of all cases presented in this thesis. Thus, it seems that mobile processing could certainly play an important role in biomass' contribution to the renewable energy portfolio in the southeastern United States.

For future studies, it might be interesting to consider both mobile and fixed processing options simultaneously rather than producing separate models and comparing the relative merits of the two alternatives. It might be interesting to allow for the selection of both mobile and centralized processing options within the same design. That is, locations with large concentrations of available cropland acres and appreciable switchgrass yields could have large centralized facilities, while mobile process units could service the areas in which biomass harvests are sparser. Such a model would being able to exploit both the benefits of economies of scale associated with fixed processing and the flexibility and decreased transportation costs (particular in areas further from fixed processing facilities) associated with mobile processing.

Another item to explore in future studies is maximum planting policies. For the scenarios presented in this chapter, up to 10% of available cropland at each potential harvest location can be planted. For future work, perhaps other planting policies could be considered. Perhaps the volatility in public policy with changing political regimes as it relates to bioenergy could be explored as another source of uncertainty in addition to uncertainty in switchgrass yields.

CHAPTER 5 Conclusions and Recommendations

According to the Billion Ton study, biomass production can play an important role in reaching the biofuel production targets set by the Energy Independence and Security ACT (EISA, 2007). In light of this, there has been a wealth of previous work in the area of bio-refinery network design, much of which has focused on examining the tradeoffs between economies of scale and feedstock transportation costs. That is, smaller more distributed facilities benefit from lower transportation costs from farmgate to biorefienry at the expense of higher fixed production costs, while larger centralized production facilities benefit from economies of scale at the expense of transporting biomass potentially large distances. This thesis expands upon this analysis by considering an alterative supply chain configuration that takes advantage of the attractive features of both distributed and centralized production facilities. In particular, this thesis examines the possibility of using smaller scale mobile processing units to convert feedstock into crude bio-oil via fast pyrolysis. By transporting liquid bio-oil instead of less energy dense solid biomass, transportation costs are decreased. Moreover, one can benefit from economies of scale by upgrading the crude bio oil within existing petroleum infrastructure. In addition to considering mobile processing, this thesis also expands upon the traditional biorefinery network design problem by exploring the impact of varying weather patterns on biorefinery network performance in both present and future climate scenarios. This was achieved by projecting switchgrass yields (model crop used in this study) using climate model output data.

In chapter 2, deterministic models for both mobile and centralized processing are introduced. The region of study includes 1908 potential harvest locations throughout the southeastern United States, 7 pipeline accessible terminals, and 1 final processing location at which crude bio-oil can be upgraded to a transportation grade fuel. Decisions common to both the mobile and centralized network design are the location and scheduling of planting and harvesting decisions, the scheduling of biomass conversion, and the scheduling of pipeline transportation of crude bio oil from the 7 pipeline accessible terminals to the final processing facility. However, for the mobile design, small mobile units travel from harvest location to harvest location and perform an initial processing step, fast pyrolysis. In contrast, for the centralized network design, harvested biomass is transported from harvest locations to selected stationary processing facilities for initial processing. Both the mobile and centralized models are quite large, since mobile units (two capacity options) can process or travel among any of the 1908 potential harvesting locations during each of the 12 months in the planning horizon, and the centralized processing design includes 1908 candidate biorefienry locations (four capacity options).

Chapter 2 explored several deterministic scenarios using switchgrass yield projections from both present and future climate scenarios. The first scenarios involved fixing the switchgrass yield at each location to it's 34 year average (1979-2012) and varying the fraction of available cropland that could be planted at each location. In all cases, the centralized design performed better (in terms of NPV) than the mobile processing design, marginally so when the fraction of available cropland available for planting was low (1 and 2 percent), while the performance gap increased as the maximum planting fraction increased (5,10,and 20 percent). At higher planting fractions, the unit transportations costs ($/ton of biomass processed) for centralized processing decreased, while unit transportation costs remained relatively constant for mobile processing as planting fraction increased. For the deterministic case, the lower unit transportation costs offered by the mobile design did not overcome the higher unit production costs ($/ton of biomass processed) incurred relative to centralized processing. The final scenarios examined in chapter 2 involved fixing the fraction of available cropland that can be planted to 10% and modeling both mobile and centralized networks using projected crop yields for 2008-2012 and 2048-2052. In general, the NPV of the mobile design is roughly 75% of that of the centralized design. The NPV of the future scenarios (2048-2052) is roughly 83% of that of the current crop yield scenarios (2008-2012) for both mobile and centralized designs.

Recall that the projected yields at each of the locations in the region of study used as part of the optimization models are derived from crop yield modeling that was conducted in this thesis. Chapter 3 detailed this effort and summarizes previous switchgrass crop yield modeling studies. Both mechanistic and empirical crop yield models were trained using climate model output data and field trial data. The mechanistic model was used to produce yield model projections at each of 1908 potential harvest locations in this study for the years 1979-2012, and 2048-2052. Variables used in this modeling effort include daily temperature, solar radiation, and soil moisture data as well as site specific soil properties such as field capacity and wilting point. The NARR provided the daily weather data, while a collaborator provided the weather data for future scenarios using the WRF model. Soil properties were provided by the Dunne Soil dataset. While the spatial distribution of switchgrass yields varied between the mechanistic and empirical models, the qualitative ranking of crop yields is equivalent for years 2048-2052 and 2008-2012. Projected crop yields were in general lower in future climate scenarios, suggesting that it may be more difficult to meet biofuel production targets in future climate scenarios in the absence of cultivar improvements.

In Chapter 4, the optimization models presented in Chapter 2 are revisited. However, in the context of Chapter 4, they are presented as two-stage planning problems that maximize the NPV of first stage decisions and the expected value of second stage decisions. For both mobile and centralized network designs, switchgrass planting is considered a first stage decision, as switchgrass is a perennial crop with a typical stand life of 10 years. For the fixed processing case, the size and location of biorefineries is also considered a first stage decision, while for the mobile processing case, processing capacity is a second stage decision, which is not fixed throughout the planting horizon. This is arguably a much more realistic scenario than the models presented in Chapter 2.

The first two-stage models presented in chapter 4 included two 5 year planning horizons representing present (2008-2012) and future (2048-2052) scenarios in which up to 10% of available cropland could be planted. In this case, the NPV of the mobile processing design was roughly 80% of fixed processing NPV. However, when the planning horizon is extended to mirror the typical switchgrass stand life of 10 years, the mobile processing design performed better than the centralized processing design. Specifically, the NPV for the fixed processing design is 75%, 48%, and 37% of that of the mobile processing design for years 1979-1988,1989-1998, and 1999-2008 respectively.

In the most realistic scenario, in which a two-stage stochastic 10 year planning horizon is considered, the mobile processing design shows great promise when compared to the fixed processing design as the inherent flexibility of the mobile processing design allows it to adjust capacity on an annual basis in response to varying crop yields. Moreover, since mobile processing is in a state of relative infancy compared to large-scale pyrolysis, it isn’t unreasonable to expect future decreases in mobile pyrolysis production with increased adoption, and perhaps future-modelling efforts should include projected future decreases in production costs with increased production of mobile units. Overall, biofuel production via fast pyrolysis from both mobile and fixed bio-refinery network designs seems to be a profitable avenue through which to achieve the biofuel production targets outlined in the Energy Security and Independence Act. Ultimately, the ideal solution may a combination of both fixed and mobile processing, and an optimization model that considers both options simultaneously may be a good direction for future work.

APPENDIX

Mobile Processing Code: Deterministic

```
$TITLE Optimal Design for Biomass Processing and Distribution Network


set i /
$include setreal.inc
/;
alias(i,ip);
set t
/1*14/;

alias(t,tp);
set r
/farm, refinery,terminal/;

set d tasks
/
plant
harvest
proc
wait

tran_come

/;
alias(d,dp);
set k resources
/
planted
harvested
oil_gal
coming
going
ready
char_ton
MMBTU
clean
dirty
switch_small
switch_med
final_oil
/;

set k3(k)
/
oil_gal
char_ton
MMBTU
final_oil
/;
set make_k(k)
```

```
/
switch_small
switch_med
/;

set z size
/
switch
small
med
/;

set p
/
b
a
/;

alias(i,ip);
*alias(t,tp);








set real_arcs(ip,i)
/
$include real_arcs.inc
/;



parameter c_transport1(ip,i)
/
$include cost_100max.inc
/;



parameter central_cost(i)
/
$include terminal_final.inc
/;

parameter pipeline_cost(i)
/
$include pipeline_cost.inc
/;

set f(i)
/
$include set_real2.inc
/;

set l(i)
/
PASCAGOULA_30
/;
set regions
```

```
/
$include terminal_set.inc
/;

parameter region_name(i)
/
$include region_name.inc
/;

scalar region_live;



region_live = 1;


set term_seti
/
$include term_set.inc
/;

set years/1978*2012/;


parameter yield_data(i);

parameter all_yields(i,years)
/
$include all_yields.inc
/;

set g(f);

set all_sets(f,regions)
/
$include all_sets.inc
/;

g(f) = all_sets(f,'211_79');
yield_data(f) = all_yields(f,'1978');

alias(g,gp);


parameter yielda(f)
/
$include yielda1983.inc
/;

parameter region_rank(regions)
/
206_86 1
218_89 2
203_90 3
232_92 4
243_93 5
248_105 6
211_79 7
/;
parameter yieldb(f)
/
$include avgyieldreal.inc
/;
```

```
parameter yieldc(f)
/
$include yielda2005.inc
/;

parameter Land(i)
/
$include landreal.inc
/;

set procset(z)
/
small
med
/;

set procdo(d)
/
proc
tran_come
/;
parameter lat(i)
/
$include lat.inc
/;
parameter lon(i)
/
$include lon.inc
/;



set term(i)
/
$include terminal_set.inc
/;


set term_set(i,ip)
/
$include terminal_set1.inc
/;


Variables
npv;

positive variables
S(i,k,t)
S1(i,k)
S2(k,t)
De(k,t)
B(i,d,z,t)
Tran(ip,i,k,t)

po
B_tran(k,t)
Deli2(i,k)
S2(k,t)
extra(i,procdo,procset,t)
B1(i,d,z,t);

integer variables
Si(i,k,z,t)
```

```
move(i,dp,d,z,t)
moves(procset)
Bi(i,d,z,t)
Deli(procset)

E(f)


Si1(i,k,d,z,t)
Sid(i,k,d,z,t)
N_tran(ip,i,z,t);


Equations

proc1(i, procset,t)
proc2(i,procset,t)

har3(i,t)
har1(i,t)

oil1(i,t)
oil2(i,t)
units1(procset)
units2(i,procset,t)
planted1(i,t)
planted2(i,t)
planted3(i,t)

units22(i,procset,t)
planted4(i,t)
processed3(i,t)
*processed31(t)
*oil3(i,t)
*oil4(i,t)
costy
plea(i)
proc7(i,procset,t)
proc8(i,procset,t)

****************************
set mp /1*5/;
scalar maxp;

parameter caps(mp)
/
1 0.01
2 0.02
3 0.05
4 0.1
5 0.2
/;
parameter acres1(i)
/
$include acres1.inc
/;
maxp = caps('1');
deli.up('small') = 5000;
deli.up('med') = 5000;
alias(i,ip);

parameter beta(t);

beta('1') = 0.95;
```

```
beta('2') = 1.0;
beta('3') = 0.95;


*ready(g,t)$(ord(t) ge 2) .. S(g,'ready',t) =e= S(g,'ready',t-1) -
B(g,'plant','switch',t);
*ready1(g) .. S(g,'ready','1') =e= 1 ;

set costout /1*20/;
plea(g) .. B(g,'plant','switch','1') =l= maxp;
planted1(g,t)$((ord(t) eq 1)  ) .. B(g,'harvest','switch',t) =l=
B(g,'plant','switch','1');
planted2(g,t)$(ord(t) eq 2   ) ..  B(g,'harvest','switch',t) +
B(g,'harvest','switch',t-1) =l= B(g,'plant','switch','1');
planted3(g,t)$(ord(t) eq 3  ) ..  B(g,'harvest','switch',t) +
B(g,'harvest','switch',t-1) + B(g,'harvest','switch',t-2) =l=
B(g,'plant','switch','1');
planted4(g,t)$(ord(t) ge 4 )  ..  B(g,'harvest','switch',t)  =e= 0;

parameter cnvt(k3)
/
oil_gal 135
char_ton .28
MMBTU 17.55
/;

parameter cvtf(k3)
/
oil_gal 1
char_ton 0.002074
MMBTU .13
/;
parameter arc_pay2(f)
/
$include arc_pay2.inc
/;
$ontext
parameter max(f)
/
$include max.inc
/;
$offtext
har3(g,t)$(ord(t) ge 2)   .. S(g,'harvested',t) =e= (S(g,'harvested',t-
1)*.99125) + (B(g,'harvest','switch',t-1)*beta(t-
1)*Yield_data(g))*0.446*Land(g) -
sum((procdo,procset),B(g,procdo,procset,t));


har1(g,t)$(ord(t) eq 1 )  .. S(g,'harvested',t)  =e=  0 -
sum((procdo,procset),B(g,procdo,procset,t));



oil1(g,t)$((ord(t) eq 1)   ) .. S(g,'final_oil',t) =e=  0 -
sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t)) + sum(gp$(term_set(gp,g) and (not
term(gp)) and (term(g))),Tran(gp,g,'final_oil',t)) -
Tran(g,'PASCAGOULA_30','final_oil',t)$term(g);
oil2(g,t)$((ord(t) ge 2)    ) .. S(g,'final_oil',t) =e=
S(g,'final_oil',t-1) + sum((procdo,procset),B(g,procdo,procset,t-
1)*.8)- sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t)) + sum(gp$(term_set(gp,g) and (not
term(gp)) and (term(g))),Tran(gp,g,'final_oil',t)) -
Tran(g,'PASCAGOULA_30','final_oil',t)$term(g) ;
```

```
processed3(i,t)$(l(i) ) .. S(i,'final_oil',t) =e= S(i,'final_oil',t-
1)$(ord(t) ge 2) + sum((g)$(term(g)),Tran(g,i,'final_oil',t));


parameter maxoo(procset);

maxoo('med') = 3000;
maxoo('small') = 3000*.5;

units1(procset) .. Sum(g,Si(g,'clean',procset,'1'))  =e= Deli(procset);


units2(g,procset,t)$(ord(t) ge 2) .. Si(g,'clean',procset,t) =e=
Si(g,'clean',procset,t-1)  +
sum(gp$(real_arcs(gp,g)),N_tran(gp,g,procset,t)) +
Bi(g,'wait',procset,t)  - Bi(g,'tran_come',procset,t);
units22(g,procset,t)$(ord(t) ge 2) .. Bi(g,'tran_come',procset,t-
1)$(ord(t) ge 3)  - sum(gp$(real_arcs(g,gp) ),N_tran(g,gp,procset,t)) +
Bi(g,'proc',procset,t-1)$(ord(t) ge 3) - Bi(g,'proc',procset,t) -
Bi(g,'wait',procset,t) =e= 0;
parameter maxdo(procset);

maxdo('med') = 1;
maxdo('small') = 0.5;

parameter tran_max(procset)
/
small 1100
med 2200
/;

parameter arc_cap(i,ip)
/
$include arc_cap.inc
/;




proc1(g, procset,t) .. B(g,'proc',procset,t) =l=
Bi(g,'proc',procset,t)*maxdo(procset)*3000  ;
proc2(g, procset,t) .. B(g,'proc',procset,t) =g=
Bi(g,'proc',procset,t)*maxdo(procset)*3000*.1;


proc7(g,procset,t) .. B(g,'tran_come',procset,t) =l=
Bi(g,'tran_come',procset,t)*maxdo(procset)*2600;
proc8(g,procset,t) .. B(g,'tran_come',procset,t) =g=
Bi(g,'tran_come',procset,t)*maxdo(procset)*2600*.1;
parameter terminal_b(f)
/
$include terminal_b.inc
/;

parameter procvar(procset)
/
med 164
small 108
/;

parameter procfix(procset)
```

```
/
med 21000
small 10500
/;

parameter costset(procset)
/
med 76000
small 50000
/;

parameter costbig(procset)
/
med 131000
small 87000
/;

parameter costtran(procset)
/
med 3
small 2
/;

set doplant(d)
/
plant
harvest
/;

parameter costdoplant(doplant)
/
plant 434
harvest 275
/;


parameter cost1(k)
/
harvested 434
final_oil 870000
/;

parameter chold(k)
/
harvested 0.03
/;
$ontext
parameter mmbtu_value(f,l)
/
$include mmbtu_val.inc
/;
$offtext
parameter procy(procset)
/
small 7700
med 15400
/;

parameter fix(procset)
/
small 424
med 528
/;
```

```
parameter fix1(procset)
/
small 1271000
med 1583000
/;

parameter tran3(procset)
/
small 2
med 3
/;

parameter cost_ref(i)
/
$include cost_ref.inc
/;

parameter cost_term(ip,i)
/
$include cost_term.inc
/;

parameter cost_ref1(i)
/
$include cost_ref1.inc
/;

parameter cost_term1(i)
/
$include terminal_cost.inc
/;

parameter miles_pipe1(i);


set kdo(k)
/
coming
going
/;

miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');


set type
/
oil_val
variable_proc
fix_tran
unit_cost
char_val
oil_tran_term
oil_tran_truck
plant_cost
variable_tran
/;

variable cost(type);
```

```
equations
cost11
cost2
cost3
cost4
cost5
cost6
cost7
cost8
cost9;

cost11 .. cost('oil_val') =e= sum(l,S(l,'final_oil','14'))*241.8;
cost2 .. cost('variable_proc') =e= -1*sum((g,procset,procdo,t),
B(g,procdo,procset,t))*8.61;

cost5 .. cost('char_val') =e= 1*sum((g,procset,procdo,t),
B(g,procdo,procset,t))*6;

cost3 .. cost('fix_tran') =e= -
1*sum((real_arcs(g,gp),procset,t),N_tran(gp,g,procset,t)*fix(procset))
- sum((g,procset,t),Bi(g,'wait',procset,t)*fix(procset));

cost4 .. cost('unit_cost') =e= -1*sum((procset),
Deli(procset)*fix1(procset));

cost6 .. cost('oil_tran_term') =e= -
1*sum((g,l,t)$(term(g)),Tran(g,l,'final_oil',t)*pipeline_cost(g)*0.0161
);

cost7 .. cost('oil_tran_truck') =e= -1*sum((g,gp,t)$((term_set(g,gp)
and term(gp))),Tran(g,gp,'final_oil',t)*cost_term1(g)*.1);
cost8 .. cost('plant_cost') =e= -
1*sum((g,t),B(g,'plant','switch',t)*Land(g))*322;

cost9 .. cost('variable_tran') =e= -
1*sum((real_arcs(g,gp),procset,t),N_tran(gp,g,procset,t)*(
tran3(procset)*(1/.62)*c_transport1(g,gp)));
costy .. npv =e= sum((type), cost(type));


option lp = cplex;
option mip = cplex;



parameter miles_pipe1(i);
miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');
parameter miles_term1(i)
/
$include terminal_cost.inc
/;

parameter B_plant(regions,years,mp,i);
parameter B_plant_r(years,mp,i);
parameter miles_term(regions,years,mp,i,t);
parameter miles_term_t(regions,years,mp,i);
parameter miles_term_f(regions,years,mp);
```

```
parameter miles_pipe(regions,years,mp,i,t);
parameter miles_pipe_t(regions,years,mp,i);
parameter miles_pipe_f(regions,years,mp);


parameter miles_unit(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t(regions,years,mp,ip,i,procset);
parameter miles_unit_f(regions,years,mp,procset);
parameter miles_unit_r(years,mp,procset);

parameter miles_unit_num(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t_num(regions,years,mp,ip,i,procset);
parameter miles_unit_f_num(regions,years,mp,procset);
parameter miles_unit_r_num(years,mp,procset);


parameter acres(regions,years,mp,i,t);
parameter acres_t_1(regions,years,mp,i);
parameter acres_t(regions,years,mp,i);
parameter acres_f(regions,years,mp);
parameter acres_r(years,mp);
parameter cost_dat(regions, years,mp,type);
parameter cost_dat_1(years,mp,type);
parameter tons(regions,years,mp,i,t);
parameter tons_t(regions,years,mp,i);
parameter tons_f(regions,years,mp);
parameter tons_r(years,mp);

parameter npvv(regions,years,mp);


parameter Tranv(regions,years,mp,ip,i,k,t);
parameter Tranv_t(regions,years,mp,ip,i,k);
parameter Tranv_f(regions,years,mp,k);
parameter Tranv_r(years,mp,k);

parameter Bv(regions,years,mp,i,d,z,t);
parameter Bv_t(regions,years,mp,i,d,z);
parameter Bv_f(regions,years,mp,d,z);
parameter Bv_r(years,mp,d,z);

parameter Biv(regions,years,mp,i,d,procset,t);
parameter Biv_t(regions,years,mp,i,d,procset);
parameter Biv_f(regions,years,mp,d,procset);
parameter Biv_r(years,mp,d,procset);

parameter Nv(regions,years,mp,ip,i,procset,t);
parameter Nv_t(regions,years,mp,ip,i,procset);
parameter Nv_f(regions,years,mp,procset);
parameter Nv_r(years,mp,procset);

parameter deliv(regions,years,mp,procset)


parameter Sv(regions,years,mp,i,k,t);
parameter Sv_t(regions,years,mp,i,k);
parameter Sv_f(regions,years,mp,k);

parameter Siv(regions,years,mp,i,k,z,t);
parameter Siv_t(regions,years,mp,i,k,z);
parameter Siv_f(regions,years,mp,k,z);
```

```
model model1 /all/;
loop((regions,years,mp)$((ord(years) eq 1) and (ord(mp) eq 4) ),
g(f) = all_sets(f,regions);
maxp = caps(mp);

S.l(i,k,t) = 0;
Si.l(i,k,z,t) = 0;
B.l(i,d,z,t) = 0;
npv.l = 0;
deli.l(procset) = 0;
Bi.l(i,d,z,t) = 0;
Tran.l(ip,i,k,t) = 0;
N_tran.l(ip,i,z,t) = 0;

yield_data(f) = all_yields(f,years);
 solve model1 using mip maximizing npv;

Sv(regions,years,mp,i,k,t) = S.l(i,k,t);
Sv_t(regions,years,mp,i,k) = sum(t,S.l(i,k,t));
Sv_f(regions,years,mp,k) = sum((i,t), S.l(i,k,t));

Siv(regions,years,mp,i,k,z,t) = Si.l(i,k,z,t);
Siv_t(regions,years,mp,i,k,z) = sum(t,Si.l(i,k,z,t));
Siv_f(regions,years,mp,k,z) = sum((i,t), Si.l(i,k,z,t));

miles_term(regions,years,mp,i,t) =
sum((procdo,procset)$B.l(i,procdo,procset,t),B.l(i,procdo,procset,t)*mi
les_term1(i)*.1);
miles_term_t(regions,years,mp,i) =
sum((t,procdo,procset)$B.l(i,procdo,procset,t),B.l(i,procdo,procset,t)*
miles_term1(i)*.1);
miles_term_f(regions,years,mp) =
sum((i,t,procdo,procset)$B.l(i,procdo,procset,t),
B.l(i,procdo,procset,t)*miles_term1(i)*.1);

cost_dat(regions,years,mp,type) = cost.l(type);

miles_pipe(regions,years,mp,i,t) =
sum((procdo,procset)$B.l(i,procdo,procset,t),B.l(i,procdo,procset,t)*mi
les_pipe1(i)*0.0161);
miles_pipe_t(regions,years,mp,i) =
sum((procdo,procset,t)$B.l(i,procdo,procset,t),
B.l(i,procdo,procset,t)*miles_pipe1(i)*0.0161);
miles_pipe_f(regions,years,mp) =
sum((procdo,procset,i,t)$B.l(i,procdo,procset,t),
B.l(i,procdo,procset,t)*miles_pipe1(i)*0.0161);


miles_unit_num(regions,years,mp,ip,i,procset,t) =
N_tran.l(ip,i,procset,t);
miles_unit_t_num(regions,years,mp,ip,i,procset) =
sum(t$N_tran.l(ip,i,procset,t), N_tran.l(ip,i,procset,t));
miles_unit_f_num(regions,years,mp,procset) =
sum((t,ip,i)$N_tran.l(ip,i,procset,t),N_tran.l(ip,i,procset,t));

miles_unit(regions,years,mp,ip,i,procset,t) =
N_tran.l(ip,i,procset,t)*c_transport1(i,ip)*tran3(procset);
miles_unit_t(regions,years,mp,ip,i,procset) =
sum(t$N_tran.l(ip,i,procset,t),
N_tran.l(ip,i,procset,t)*c_transport1(i,ip)*tran3(procset)*(1/.62));
miles_unit_f(regions,years,mp,procset) =
sum((t,ip,i)$N_tran.l(ip,i,procset,t),N_tran.l(ip,i,procset,t)*c_transp
ort1(i,ip)*tran3(procset)*(1/.62));
```

```
B_plant(regions,years,mp,i) =
sum(t$B.l(i,'plant','switch',t),B.l(i,'plant','switch',t));

npvv(regions, years,mp) = npv.l;




Tranv(regions,years,mp,ip,i,k,t) = Tran.l(ip,i,k,t);
Tranv_t(regions,years,mp,ip,i,k) = sum(t$Tran.l(ip,i,k,t),
Tran.l(ip,i,k,t));
Tranv_f(regions,years,mp,k) =
sum((t,ip,i)$Tran.l(ip,i,k,t),Tran.l(ip,i,k,t));


Bv(regions,years,mp,i,d,z,t) = B.l(i,d,z,t);
Bv_t(regions,years,mp,i,d,z) = sum(t$B.l(i,d,z,t),B.l(i,d,z,t));
Bv_f(regions,years,mp,d,z) = sum((i,t)$B.l(i,d,z,t), B.l(i,d,z,t));


Biv(regions,years,mp,i,d,procset,t) = Bi.l(i,d,procset,t);
Biv_t(regions,years,mp,i,d,procset) = sum((t)$Bi.l(i,d,procset,t),
Bi.l(i,d,procset,t));
Biv_f(regions,years,mp,d,procset) = sum((i,t)$Bi.l(i,d,procset,t),
Bi.l(i,d,procset,t));



Nv(regions,years,mp,ip,i,procset,t) = N_tran.l(ip,i,procset,t);
Nv_t(regions,years,mp,ip,i,procset) = sum(t$N_tran.l(ip,i,procset,t),
N_tran.l(ip,i,procset,t));
Nv_f(regions,years,mp,procset) = sum((ip,i,t)$N_tran.l(ip,i,procset,t),
N_tran.l(ip,i,procset,t));


deliv(regions,years,mp,procset) = deli.l(procset);
acres(regions,years,mp,i,t) = B.l(i,'plant','switch',t)*Land(i);
acres_t(regions,years,mp,i) =
sum(t$B.l(i,'plant','switch',t),B.l(i,'plant','switch',t)*Land(i));
acres_t_1(regions,years,mp,i) =
sum(t$B.l(i,'plant','switch',t),B.l(i,'plant','switch',t)*1000);
acres_f(regions,years,mp) = sum((i,t)$B.l(i,'plant','switch',t),
B.l(i,'plant','switch',t)*Land(i));

tons(regions,years,mp,i,t) =
B.l(i,'harvest','switch',t)*Land(i)*yield_data(i);
tons_t(regions,years,mp,i) =
sum(t$B.l(i,'harvest','switch',t),B.l(i,'harvest','switch',t)*Land(i)*y
ield_data(i));
tons_f(regions,years,mp) = sum((i,t)$B.l(i,'harvest','switch',t),
B.l(i,'harvest','switch',t)*Land(i)*yield_data(i));
);

parameter npvv_r(years,mp);
parameter miles_pipe_r(years,mp);
parameter miles_term_r(years,mp);
miles_pipe_r(years,mp) = sum(regions, miles_pipe_f(regions,years,mp));
miles_term_r(years,mp) = sum(regions,miles_term_f(regions,years,mp));
cost_dat_1(years,mp,type) = sum(regions,
cost_dat(regions,years,mp,type));
parameter deliv_r(years,mp,procset);
miles_term_r(years,mp) = sum(regions,miles_term_f(regions,years,mp));
miles_pipe_r(years,mp) = sum(regions,miles_pipe_f(regions,years,mp));
```

```
miles_unit_r(years,mp,procset) = sum(regions,
miles_unit_f(regions,years,mp,procset));
miles_unit_r_num(years,mp,procset) = sum(regions,
miles_unit_f_num(regions,years,mp,procset));
tons_r(years,mp) = sum(regions, tons_f(regions,years,mp));
npvv_r(years,mp) = sum(regions, npvv(regions,years,mp));
Tranv_r(years,mp,k) = sum(regions, Tranv_f(regions,years,mp,k));
Bv_r(years,mp,d,z) = sum(regions, Bv_f(regions,years,mp,d,z));
Biv_r(years,mp,d,procset) = sum(regions,
Biv_f(regions,years,mp,d,procset));
Nv_r(years,mp,procset) = sum(regions, Nv_f(regions,years,mp,procset));
deliv_r(years,mp,procset) = sum(regions,
deliv(regions,years,mp,procset));
B_plant_r(years,mp,i) = sum(regions, B_plant(regions,years,mp,i));
acres_r(years,mp) = sum(regions, acres_f(regions,years,mp));


$ontext
1       Acres
2       Tons
3       Planting & Harvest Costs
4       Variable Processing Costs
5       Processor Med
6       Porcessor Small
7       Capacity
8       ton-miles oil truck
9       ton-miles oil pipeline
10      Cost Oil Truck
11      Cost Oil Pipeline
12      Unit Transport Costs
13      Processor Cost
14      Setup Costs
15      Num Moves Small
16     Num Moves Med
17      Oil Value
18      char
19      gas value
20      NPV

$offtext



parameter cost22(costout,years,mp);
cost22('1',years,mp) = acres_r(years,mp);
cost22('2',years,mp) = tons_r(years,mp);
cost22('3',years,mp) = acres_r(years,mp)*322;
cost22('4',years,mp) = sum((procdo,procset),
Bv_r(years,mp,procdo,procset))*15.57;
cost22('5',years,mp) = deliv_r(years,mp,'small');
cost22('6',years,mp) = deliv_r(years,mp,'med');
cost22('7',years,mp) = deliv_r(years,mp,'small')*1500*12 +
deliv_r(years,mp,'med')*3000*12;
cost22('8',years,mp) = miles_pipe_r(years,mp)*(1/0.0161);
cost22('9',years,mp) = miles_term_r(years,mp)*(1/0.1);
cost22('10',years,mp) = miles_pipe_r(years,mp);
cost22('11',years,mp) = 700;
cost22('12',years,mp) = miles_term_r(years,mp);
cost22('13',years,mp) = sum(procset,miles_unit_r(years,mp,procset));
cost22('14',years,mp) = sum(procset,miles_unit_r(years,mp,procset)) +
sum(procset,Biv_r(years,mp,'wait',procset)*fix(procset));
cost22('15',years,mp) = miles_unit_r_num(years,mp,'small');
cost22('16',years,mp) = miles_unit_r_num(years,mp,'med');
cost22('17',years,mp) = tons_r(years,mp)*.8*241.8;
```

```
cost22('18',years,mp) = tons_r(years,mp)*.1*.40;
cost22('19',years,mp) = tons_r(years,mp)*.1*20;
cost22('20',years,mp) = npvv_r(years,mp);

file f_cost_22 /cost_2.csv/;
f_cost_22.pc = 5;
put f_cost_22;
loop((costout,years,mp)$cost22(costout,years,mp),
put costout.te(costout), years.te(years),
mp.te(mp),cost22(costout,years,mp) /;
);



file f_miles_term /miles_term.csv/;
f_miles_term.pc = 5;
put f_miles_term;
loop((regions,years,mp,i,t)$miles_term(regions,years,mp,i,t),
put regions.te(regions), years.te(years), mp.te(mp), i.te(i), t.te(t),
miles_term(regions,years,mp,i,t) /;
);
putclose;

file f_miles_term_t /miles_term_t.csv/;
f_miles_term_t.pc = 5;
put f_miles_term_t;
loop((regions,years,mp,i)$miles_term_t(regions,years,mp,i),
put regions.te(regions), years.te(years),mp.te(mp), i.te(i),
miles_term_t(regions,years,mp,i)/;
);
putclose;

file f_cost_dat/cost_dat.csv/;
f_cost_dat.pc = 5;
put f_cost_dat;
loop((regions,years,mp,type)$cost_dat(regions,years,mp,type),
put regions.te(regions), years.te(years), mp.te(mp),type.te(type),
cost_dat(regions,years,mp,type)/;
);
putclose;


file f_cost_dat1/cost_dat1.csv/;
f_cost_dat1.pc = 5;
put f_cost_dat1;
loop((years,type,mp)$cost_dat_1(years,mp,type),
put  years.te(years), mp.te(mp),type.te(type),
cost_dat_1(years,mp,type)/;
);
putclose;

file f_miles_term_f /miles_term_f.csv/;
f_miles_term_f.pc = 5;
put f_miles_term_f;
loop((regions,years,mp)$miles_term_f(regions,years,mp),
put regions.te(regions),
years.te(years),mp.te(mp),miles_term_f(regions,years,mp)/;
);
putclose;

file f_miles_term_r /miles_term_r.csv/;
f_miles_term_r.pc = 5;
put f_miles_term_r;
loop((years,mp)$miles_term_r(years,mp),
```

```
put  years.te(years),mp.te(mp),miles_term_r(years,mp)/;
);
putclose;



file f_miles_pipe /miles_pipe.csv/;
f_miles_pipe.pc = 5;
put f_miles_pipe;
loop((regions,years,mp,i,t)$miles_pipe(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
miles_pipe(regions,years,mp,i,t)/;
);
putclose;

file f_miles_pipe_t /miles_pipe_t.csv/;
f_miles_pipe_t.pc = 5;
put f_miles_pipe_t;
loop((regions,years,mp,i)$miles_pipe_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
miles_pipe_t(regions,years,mp,i)/;
);
putclose;


file f_miles_pipe_f /miles_pipe_f.csv/;
f_miles_pipe_f.pc = 5;
put f_miles_pipe_f;
loop((regions,years,mp)$miles_pipe_f(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),miles_pipe_f(regions,years,mp)/;
);
putclose;

file f_miles_pipe_r /miles_pipe_r.csv/;
f_miles_pipe_r.pc = 5;
put f_miles_pipe_r;
loop((years,mp)$miles_pipe_r(years,mp),
put years.te(years), mp.te(mp),miles_pipe_r(years,mp)/;
);
putclose;


**************************************

file f_miles_unit /miles_unit.csv/;
f_miles_unit.pc = 5;
put f_miles_unit;
loop((regions,years,mp,ip,i,procset,t)$miles_unit(regions,years,mp,ip,i
,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), procset.te(procset), t.te(t),
miles_unit(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_miles_unit_t /miles_unit_t.csv/;
f_miles_unit_t.pc = 5;
put f_miles_unit_t;
loop((regions,years,mp,ip,i,procset)$miles_unit_t(regions,years,mp,ip,i
,procset),
put  regions.te(regions), years.te(years), ip.te(ip),
i.te(i),mp.te(mp), procset.te(procset),
miles_unit_t(regions,years,mp,ip,i,procset)/;
```

```
);
putclose;


file f_miles_unit_f /miles_unit_f.csv/;
f_miles_unit_f.pc = 5;
put f_miles_unit_f;
loop((regions,years,procset,mp)$miles_unit_f(regions,years,mp,procset),
put  regions.te(regions), years.te(years),procset.te(procset),
miles_unit_f(regions,years,mp,procset)/;
);
putclose;

file f_miles_unit_r /miles_unit_r.csv/;
f_miles_unit_r.pc = 5;
put f_miles_unit_r;
loop((years,procset,mp)$miles_unit_r(years,mp,procset),
put years.te(years), mp.te(mp),procset.te(procset),
miles_unit_r(years,mp,procset)/;
);
putclose;
*******************************


file f_miles_unit_num /miles_unit_num.csv/;
f_miles_unit_num.pc = 5;
put f_miles_unit_num;
loop((regions,years,mp,ip,i,procset,t)$miles_unit_num(regions,years,mp,
ip,i,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), procset.te(procset), t.te(t),
miles_unit_num(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_miles_unit_t_num /miles_unit_t_num.csv/;
f_miles_unit_t_num.pc = 5;
put f_miles_unit_t_num;
loop((regions,years,mp,ip,i,procset)$miles_unit_t_num(regions,years,mp,
ip,i,procset),
put  regions.te(regions), years.te(years), ip.te(ip),
i.te(i),mp.te(mp), procset.te(procset),
miles_unit_t_num(regions,years,mp,ip,i,procset)/;
);
putclose;


file f_miles_unit_f_num /miles_unit_f_num.csv/;
f_miles_unit_f_num.pc = 5;
put f_miles_unit_f_num;
loop((regions,years,procset,mp)$miles_unit_f_num(regions,years,mp,procs
et),
put  regions.te(regions), years.te(years),procset.te(procset),
miles_unit_f_num(regions,years,mp,procset)/;
);
putclose;

file f_miles_unit_r_num /miles_unit_r_num.csv/;
f_miles_unit_r_num.pc = 5;
put f_miles_unit_r_num;
loop((years,procset,mp)$miles_unit_r_num(years,mp,procset),
put years.te(years), mp.te(mp),procset.te(procset),
miles_unit_r_num(years,mp,procset)/;
);
```

```
putclose;
*******************************


file f_acres /acres.csv/;
f_acres.pc = 5;
put f_acres;
loop((regions,years,mp,i,t)$acres(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
acres(regions,years,mp,i,t)/;
);
putclose;

file f_acres_t /acres_t.csv/;
f_acres_t.pc = 5;
put f_acres_t;
loop((regions,years,mp,i)$acres_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
acres_t(regions,years,mp,i)/;
);
putclose;


file f_acres_f /acres_f.csv/;
f_acres_f.pc = 5;
put f_acres_f;
loop((regions,years,mp)$acres_f(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),acres_f(regions,years,mp)/;
);
putclose;

file f_acres_r /acres_r.csv/;
f_acres_r.pc = 5;
put f_acres_r;
loop((years,mp)$acres_r(years,mp),
put years.te(years),mp.te(mp), acres_r(years,mp)/;
);
putclose;
*******************************************


file f_tons /tons.csv/;
f_tons.pc = 5;
put f_tons;
loop((regions,years,mp,i,t)$tons(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
tons(regions,years,mp,i,t)/;
);
putclose;

file f_tons_t /tons_t.csv/;
f_tons_t.pc = 5;
put f_tons_t;
loop((regions,years,mp,i)$tons_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
tons_t(regions,years,mp,i)/;
);
putclose;


file f_tons_f /tons_f.csv/;
f_tons_f.pc = 5;
put f_tons_f;
```

```
loop((regions,years,mp)$tons_f(regions,years,mp),
put  regions.te(regions), years.te(years),mp.te(mp),
tons_f(regions,years,mp)/;
);
putclose;

file f_tons_r /tons_r.csv/;
f_tons_r.pc = 5;
put f_tons_r;
loop((years,mp)$tons_r(years,mp),
put years.te(years),mp.te(mp), tons_r(years,mp)/;
);
putclose;
**************************************************


file f_npvv /npvv.csv/;
f_npvv.pc = 5;
put f_npvv;
loop((regions,years,mp)$npvv(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),npvv(regions,years,mp)/;
);
putclose;

file f_npvv_r /npvv_r.csv/;
f_npvv_r.pc = 5;
put f_npvv_r;
loop((years,mp)$npvv_r(years,mp),
put years.te(years),mp.te(mp), npvv_r(years,mp)/;
);
putclose;
*******************************

file f_Tranv /Tranv.csv/;
f_Tranv.pc = 5;
put f_Tranv;
loop((regions,years,mp,ip,i,k,t)$Tranv(regions,years,mp,ip,i,k,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), t.te(t), k.te(k),lon(ip),lat(ip),lon(i),lat(i),
Tranv(regions,years,mp,ip,i,k,t)/;
);
putclose;

file f_Tranv_t /Tranv_t.csv/;
f_Tranv_t.pc = 5;
put f_Tranv_t;
loop((regions,years,mp,ip,i,k)$Tranv_t(regions,years,mp,ip,i,k),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
ip.te(ip),k.te(k),  Tranv_t(regions,years,mp,ip,i,k)/;
);
putclose;


file f_Tranv_f /Tranv_f.csv/;
f_Tranv_f.pc = 5;
put f_Tranv_f;
loop((regions,years,mp,k)$Tranv_f(regions,years,mp,k),
put  regions.te(regions), years.te(years),mp.te(mp),k.te(k),
Tranv_f(regions,years,mp,k)/;
);
putclose;

file f_Tranv_r /Tranv_r.csv/;
```

```
f_Tranv_r.pc = 5;
put f_Tranv_r;
loop((years,mp,k)$Tranv_r(years,mp,k),
put years.te(years),mp.te(mp), k.te(k),Tranv_r(years,mp,k)/;
);
putclose;
************************************************************

file f_Bv /Bv.csv/;
f_Bv.pc = 5;
put f_Bv;
loop((regions,years,mp,i,d,z,t)$Bv(regions,years,mp,i,d,z,t),
put  regions.te(regions), years.te(years),mp.te(mp),i.te(i), d.te(d),
z.te(z), t.te(t), Bv(regions,years,mp,i,d,z,t), lat(i), lon(i)/;
);
putclose;

file f_Bv_t /Bv_t.csv/;
f_Bv_t.pc = 5;
put f_Bv_t;
loop((regions,years,mp,i,d,z)$Bv_t(regions,years,mp,i,d,z),
put  regions.te(regions), years.te(years), mp.te(mp),i.te(i), d.te(d),
z.te(d),  Bv_t(regions,years,mp,i,d,z)/;
);
putclose;


file f_Bv_f /Bv_f.csv/;
f_Bv_f.pc = 5;
put f_Bv_f;
loop((regions,years,mp,d,z)$Bv_f(regions,years,mp,d,z),
put  regions.te(regions), years.te(years),mp.te(mp),d.te(d), z.te(z),
Bv_f(regions,years,mp,d,z)/;
);
putclose;

file f_Bv_r /Bv_r.csv/;
f_Bv_r.pc = 5;
put f_Bv_r;
loop((years,mp,d,z)$Bv_r(years,mp,d,z),
put years.te(years),mp.te(mp), d.te(d), z.te(z), Bv_r(years,mp,d,z)/;
);
putclose;
***************************************************************

file f_Biv /Biv.csv/;
f_Biv.pc = 5;
put f_Biv;
loop((regions,years,mp,i,procdo,procset,t)$Biv(regions,years,mp,i,procd
o,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
procdo.te(procdo), procset.te(procset), t.te(t),
Biv(regions,years,mp,i,procdo,procset,t)/;
);
putclose;

file f_Biv_t /Biv_t.csv/;
f_Biv_t.pc = 5;
put f_Biv_t;
loop((regions,years,mp,i,procdo,procset)$Biv_t(regions,years,mp,i,procd
o,procset),
put  regions.te(regions), years.te(years), mp.te(mp), i.te(i),
procdo.te(procdo), procset.te(procset),
Biv_t(regions,years,mp,i,procdo,procset)/;
```

```
);
putclose;



file f_Biv_f /Biv_f.csv/;
f_Biv_f.pc = 5;
put f_Biv_f;
loop((regions,years,mp,procdo,procset)$Biv_f(regions,years,mp,procdo,pr
ocset),
put  regions.te(regions), years.te(years),mp.te(mp),procdo.te(procdo),
procset.te(procset), Biv_f(regions,years,mp,procdo,procset)/;
);
putclose;

file f_Biv_r /Biv_r.csv/;
f_Biv_r.pc = 5;
put f_Biv_r;
loop((years,mp,procdo,procset)$Biv_r(years,mp,procdo,procset),
put years.te(years), mp.te(mp),procdo.te(procdo), procset.te(procset),
Biv_r(years,mp,procdo,procset)/;
);
putclose;
***********************************************************************
******
file f_Nv /Nv.csv/;
f_Nv.pc = 5;
put f_Nv;
loop((regions,years,mp,ip,i,procset,t)$Nv(regions,years,mp,ip,i,procset
,t),
put  regions.te(regions), years.te(years), mp.te(mp)ip.te(ip), i.te(i),
t.te(t), procset.te(procset), lat(i), lon(i), lat(ip), lon(ip),
Nv(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_Nv_t /Nv_t.csv/;
f_Nv_t.pc = 5;
put f_Nv_t;
loop((regions,years,mp,ip,i,procset)$Nv_t(regions,years,mp,ip,i,procset
),
put  regions.te(regions), years.te(years), mp.te(mp),i.te(i),
ip.te(ip),procset.te(procset),  Nv_t(regions,years,mp,ip,i,procset)/;
);
putclose;


file f_Nv_f /Nv_f.csv/;
f_Nv_f.pc = 5;
put f_Nv_f;
loop((regions,years,mp,procset)$Nv_f(regions,years,mp,procset),
put  regions.te(regions),
mp.te(mp),years.te(years),procset.te(procset),
Nv_f(regions,years,mp,procset)/;
);
putclose;

file f_Nv_r /Nv_r.csv/;
f_Nv_r.pc = 5;
put f_Nv_r;
loop((years,mp,procset)$Nv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),Nv_r(years,mp,procset)/;
);
```

```
putclose;
************************************************************************
******
file f_deliv /deliv.csv/;
f_deliv.pc = 5;
put f_deliv;
loop((regions,years,mp,procset)$deliv(regions,years,mp,procset),
put  regions.te(regions),
years.te(years),mp.te(mp),procset.te(procset),
deliv(regions,years,mp,procset)/;
);
putclose;

file f_deliv_r /deliv_r.csv/;
f_deliv_r.pc = 5;
put f_deliv_r;
loop((years,mp,procset)$deliv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),deliv_r(years,mp,procset)/;
);
putclose;

************************************************************************
******
file f_Sv /f_Sv.csv/;
f_Sv.pc = 5;
put f_Sv;
loop((regions,years,mp,i,k,t)$Sv(regions,years,mp,i,k,t),
put regions.te(regions),years.te(years),mp.te(mp), i.te(i), k.te(k),
t.te(t),Sv(regions,years,mp,i,k,t)/;
);
putclose;

file f_Sv_t /f_Sv_t.csv/;
f_Sv_t.pc = 5;
put f_Sv_t;
loop((regions,years,mp,i,k)$Sv_t(regions,years,mp,i,k),
put regions.te(regions),years.te(years),mp.te(mp), i.te(i),
k.te(k),Sv_t(regions,years,mp,i,k) /;
);
putclose;

file f_Sv_f /f_Sv_f.csv/;
f_Sv_f.pc = 5;
put f_Sv_f;
loop((regions,years,mp,k)$Sv_f(regions,years,mp,k),
put regions.te(regions),years.te(years),mp.te(mp),
k.te(k),Sv_f(regions,years,mp,k) /;
);
putclose;

************************************************************************
******
file f_Siv /f_Siv.csv/;
f_Siv.pc = 5;
put f_Siv;
loop((regions,years,mp,i,k,z,t)$Siv(regions,years,mp,i,k,z,t),
put regions.te(regions),years.te(years), mp.te(mp),i.te(i), k.te(k),
z.te(z), t.te(t),Siv(regions,years,mp,i,k,z,t) /;
);
putclose;

file f_Siv_t /f_Siv_t.csv/;
f_Siv_t.pc = 5;
```

```
put f_Siv_t;
loop((regions,years,mp,i,k,z)$Siv_t(regions,years,mp,i,k,z),
put regions.te(regions),years.te(years), mp.te(mp),i.te(i), k.te(k),
z.te(z), Siv_t(regions,years,mp,i,k,z)/;
);
putclose;

file f_Siv_f /f_Siv_f.csv/;
f_Siv_f.pc = 5;
put f_Siv_f;
loop((regions,years,mp,k,z)$Siv_f(regions,years,mp,k,z),
put regions.te(regions),years.te(years), mp.te(mp),k.te(k), z.te(z),
Siv_f(regions,years,mp,k,z) /;
);
putclose;
**********************************************************************
******
file f_Bpl /f_Bpl.csv/;
f_Bpl.pc = 5;
put f_Bpl;
loop((regions,years,mp,i)$B_plant(regions,years,mp,i),
put i.te(i),regions.te(regions),years.te(years),mp.te(mp),
B_plant(regions,years,mp,i) /;
);
putclose;

file f_Bplr /f_Bplr.csv/;
f_Bplr.pc = 5;

put f_Bplr;
loop((years,mp,i)$B_plant_r(years,mp,i),
put i.te(i),years.te(years),mp.te(mp), B_plant_r(years,mp,i) /;
);
putclose;
```

Fixed Processing Code: Deterministic

```
$TITLE Optimal Design for Biomass Processing and Distribution Network

set i /
$include setreal.inc
/;
alias(i,ip);
set t
/1*14/;

alias(t,tp);
set r
/farm, refinery,terminal/;

set d tasks
/
plant
harvest
proc
wait
/;
alias(d,dp);
set k resources
/
planted
harvested
oil_gal
coming
going
ready
char_ton
MMBTU
clean
dirty
switch_small
switch_med
final_oil
/;

set k3(k)
/
oil_gal
char_ton
MMBTU
final_oil
/;
set make_k(k)
/
switch_small
switch_med
/;

set z size
/
switch
small
med
large
extra
/;

set p
```

```
/
b
a
/;


alias(i,ip);
*alias(t,tp);

set real_arcs(ip,i)
/
$include real_arcs.inc
/;



parameter c_transport1(ip,i)
/
$include cost_100max.inc
/;



parameter central_cost(i)
/
$include terminal_final.inc
/;

parameter pipeline_cost(i)
/
$include pipeline_cost.inc
/;

set f(i)
/
$include set_real2.inc
/;

set l(i)
/
PASCAGOULA_30
/;
set regions
/
$include terminal_set.inc
/;

parameter region_name(i)
/
$include region_name.inc
/;

scalar region_live;



region_live = 1;


set term_seti
/
$include term_set.inc
/;
set years /1978*2052/;
```

```
alias(years,yp);

set sc(yp)
/
2008
2009
2010
2011
2012
/;

parameter all_yields(i,sc)
/
$include all_yields.inc
/;


parameter yield_data(i);


set g(f);

set all_sets(f,regions)
/
$include all_sets.inc
/;

g(f) = all_sets(f,'211_79');
yield_data(f) = all_yields(f,'2008');

alias(g,gp);



parameter yielda(f)
/
$include yielda1983.inc
/;

parameter region_rank(regions)
/
206_86 1
218_89 2
203_90 3
232_92 4
243_93 5
248_105 6
211_79 7
/;
parameter yieldb(f)
/
$include avgyieldreal.inc
/;

parameter yieldc(f)
/
$include yielda2005.inc
/;

parameter Land(i)
/
$include landreal.inc
/;
```

```
set procset(z)
/
small
med
large
extra
/;

set procdo(d)
/
proc
/;
parameter lat(i)
/
$include lat.inc
/;
parameter lon(i)
/
$include lon.inc
/;


set term(i)
/
$include terminal_set.inc
/;


set term_set(i,ip)
/
$include terminal_set1.inc
/;


Variables
npv;

positive variables
S(i,k,t,sc)
S1(i,k)
S2(k,t)
pp(i)
De(k,t)
B(i,d,z,t,sc)
Tran(ip,i,k,t,sc)

po
B_tran(k,t)
Deli2(i,k)
S2(k,t)
extra(i,procdo,procset,t)
B1(i,d,z,t);

integer variables
Si(i,k,z,t)
move(i,dp,d,z,t)
moves(procset)
Bi(i,d,z,t)
Deli(procset)
```

```
E(f)


Si1(i,k,d,z,t)
Sid(i,k,d,z,t)
N_tran(ip,i,z,t);

Binary variables
za(i,procset);

Equations
*planted(f,t)

*demand


proc1(i,procset,t,sc)

proc2(i)


*eff(fp,f,t)

har3(i,t,sc)
har1(i,t,sc)

oil1(i,t,sc)
oil2(i,t,sc)
*units1(procset)
*units2(i,procset,t)
planted1(i,t,sc)
planted2(i,t,sc)
planted3(i,t,sc)


*units22(i,procset,t)
planted4(i,t,sc)
processed3(i,t,sc)
*processed31(t)
*oil3(i,t)
*oil4(i,t)
costy
plea(i)
*proc7(i,procset,t)
*proc8(i,procset,t)

;
****************************
set mp /1*5/;
scalar maxp;

parameter caps(mp)
/
1 0.01
2 0.02
3 0.05
4 0.1
5 0.2
/;

maxp = caps('1');
deli.up('small') = 5000;
deli.up('med') = 5000;
alias(i,ip);
```

```
parameter beta(t);

beta('1') = 0.95;
beta('2') = 1.0;
beta('3') = 0.95;


set costout /1*20/;
plea(g) .. pp(g) =l= 0.1;
planted1(g,t,sc)$((ord(t) eq 1)  ) .. B(g,'harvest','switch',t,sc) =l=
pp(g);
planted2(g,t,sc)$(ord(t) eq 2   ) ..  B(g,'harvest','switch',t,sc) +
B(g,'harvest','switch',t-1,sc) =l= pp(g);
planted3(g,t,sc)$(ord(t) eq 3  ) ..  B(g,'harvest','switch',t,sc) +
B(g,'harvest','switch',t-1,sc) + B(g,'harvest','switch',t-2,sc) =l=
pp(g);
planted4(g,t,sc)$(ord(t) ge 4 )  ..  B(g,'harvest','switch',t,sc)  =e=
0;

parameter cnvt(k3)
/
oil_gal 135
char_ton .28
MMBTU 17.55
/;

parameter cvtf(k3)
/
oil_gal 1
char_ton 0.002074
MMBTU .13
/;
parameter arc_pay2(f)
/
$include arc_pay2.inc
/;
$ontext
parameter max(f)
/
$include max.inc
/;
$offtext
har3(g,t,sc)$(ord(t) ge 2)   .. S(g,'harvested',t,sc) =e=
(S(g,'harvested',t-1,sc)*.99125) + (B(g,'harvest','switch',t-
1,sc)*beta(t-1)*all_yields(g,sc))*0.446*Land(g) +
sum(gp$(real_arcs(gp,g)),Tran(gp,g,'harvested',t-1,sc)) -
sum(gp$(real_arcs(g,gp)),Tran(g,gp,'harvested',t,sc)) -
sum((procdo,procset),B(g,procdo,procset,t,sc));


har1(g,t,sc)$(ord(t) eq 1 )  .. S(g,'harvested',t,sc)  =e=  0 -
sum((procdo,procset),B(g,procdo,procset,t,sc)) -
sum(gp$(real_arcs(g,gp)),Tran(g,gp,'harvested',t,sc));



oil1(g,t,sc)$((ord(t) eq 1)   ) .. S(g,'final_oil',t,sc) =e=  0 -
sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t,sc)) + sum(gp$(term_set(gp,g) and
(not term(gp)) and (term(g))),Tran(gp,g,'final_oil',t,sc)) -
Tran(g,'PASCAGOULA_30','final_oil',t,sc)$term(g);
oil2(g,t,sc)$((ord(t) ge 2)    ) .. S(g,'final_oil',t,sc) =e=
S(g,'final_oil',t-1,sc) + sum((procdo,procset),B(g,procdo,procset,t-
```

```
1,sc)*.8)- sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t,sc)) + sum(gp$(term_set(gp,g) and
(not term(gp)) and (term(g))),Tran(gp,g,'final_oil',t,sc)) -
Tran(g,'PASCAGOULA_30','final_oil',t,sc)$term(g) ;


processed3(i,t,sc)$(l(i) ) .. S(i,'final_oil',t,sc) =e=
S(i,'final_oil',t-1,sc)$(ord(t) ge 2) +
sum((g)$(term(g)),Tran(g,i,'final_oil',t,sc));




parameter maxoo(procset);


parameter maxdo(procset)
/
small 1225000
med 2450000
large 3675000
extra 4900000
/;

parameter costz(procset)
/
small 7728000
med 12768000
large 17808000
extra 22848000
/;


parameter tran_max(procset)
/
small 1100
med 2200
/;

parameter arc_cap(i,ip)
/
$include arc_cap.inc
/;




proc1(g,procset,t,sc) .. B(g,'proc',procset,t,sc) =l=
za(g,procset)*maxdo(procset)*(1/12);

proc2(g) .. sum(procset,za(g,procset)) =l= 1;

parameter terminal_b(f)
/
$include terminal_b.inc
/;

parameter procvar(procset)
/
med 164
small 108
/;

parameter procfix(procset)
```

```
/
med 21000
small 10500
/;

parameter costset(procset)
/
med 76000
small 50000
/;

parameter costbig(procset)
/
med 131000
small 87000
/;

parameter costtran(procset)
/
med 3
small 2
/;

set doplant(d)
/
plant
harvest
/;

parameter costdoplant(doplant)
/
plant 434
harvest 275
/;


parameter cost1(k)
/
harvested 434
final_oil 870000
/;

parameter chold(k)
/
harvested 0.03
/;
$ontext
parameter mmbtu_value(f,l)
/
$include mmbtu_val.inc
/;
$offtext
parameter procy(procset)
/
small 7700
med 15400
/;

parameter fix(procset)
/
small 424
med 528
/;
```

```
parameter fix1(procset)
/
small 1271000
med 1583000
/;

parameter tran3(procset)
/
small 2
med 3
/;

parameter cost_ref(i)
/
$include cost_ref.inc
/;

parameter cost_term(ip,i)
/
$include cost_term.inc
/;

parameter cost_ref1(i)
/
$include cost_ref1.inc
/;

parameter cost_term1(i)
/
$include terminal_cost.inc
/;

parameter miles_pipe1(i);


set kdo(k)
/
coming
going
/;

miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');


set type
/
oil_val
variable_proc
fix_tran
unit_cost
char_val
oil_tran_term
oil_tran_truck
plant_cost
variable_tran
/;

set type2(type)
```

```
/
oil_val
variable_proc
*fix_tran
*unit_cost
char_val
oil_tran_term
oil_tran_truck
*plant_cost
variable_tran/;


parameter costvz(procset)
/
small 13.7
med 11.65
large 10.65
extra 9.97
/;

equations
cost11(sc)
cost2(sc)
*cost3(sc)
cost4(sc)
cost5(sc)
cost6(sc)
cost7(sc)
cost8(sc)
cost9(sc);
variable cost(type,sc);


cost11(sc) .. cost('oil_val',sc) =e=
sum(l,S(l,'final_oil','14',sc))*241.8;
cost2(sc) .. cost('variable_proc',sc) =e= - sum((g,procset,t),
B(g,'proc',procset,t,sc)*costvz(procset));

cost4(sc) .. cost('unit_cost',sc) =e= -1*sum((g,procset),
za(g,procset)*costz(procset));
cost5(sc) .. cost('char_val',sc) =e= sum((g,procdo,procset,t)$(ord(t)
le 13), B(g,procdo,procset,t,sc)*6);

cost6(sc) .. cost('oil_tran_term',sc) =e= -
1*sum((g,l,t)$(term(g)),Tran(g,l,'final_oil',t,sc)*pipeline_cost(g)*0.0
161);

cost7(sc) .. cost('oil_tran_truck',sc) =e= -
1*sum((g,gp,t)$((term_set(g,gp) and
term(gp))),Tran(g,gp,'final_oil',t,sc)*cost_term1(g)*.1);
cost8(sc) .. cost('plant_cost',sc) =e= -1*sum((g),pp(g)*Land(g))*322;

cost9(sc) .. cost('variable_tran',sc) =e= -
1*sum((real_arcs(gp,g),t),Tran(gp,g,'harvested',t,sc)*.31*c_transport1(
gp,g));

costy .. npv =e= .2*sum((type2,sc), cost(type2,sc)) -
1*sum(g,pp(g)*Land(g))*322   -1*sum((g,procset),
za(g,procset)*costz(procset)) ;

option lp = cplex;
option mip = cplex;
```

```
parameter miles_pipe1(i);
miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');
parameter miles_term1(i)
/
$include terminal_cost.inc
/;

parameter B_plant(regions,years,mp,i);
parameter B_plant_r(years,mp,i);
parameter miles_term(regions,years,mp,i,t);
parameter miles_term_t(regions,years,mp,i);
parameter miles_term_f(regions,years,mp);


parameter miles_pipe(regions,years,mp,i,t);
parameter miles_pipe_t(regions,years,mp,i);
parameter miles_pipe_f(regions,years,mp);


parameter miles_unit(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t(regions,years,mp,ip,i,procset);
parameter miles_unit_f(regions,years,mp,procset);
parameter miles_unit_r(years,mp,procset);

parameter miles_unit_num(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t_num(regions,years,mp,ip,i,procset);
parameter miles_unit_f_num(regions,years,mp,procset);
parameter miles_unit_r_num(years,mp,procset);


parameter acres(regions,years,mp,i,t);
parameter acres_t_1(regions,years,mp,i);
parameter acres_t(regions,years,mp,i);
parameter acres_f(regions,years,mp);
parameter acres_r(years,mp);
parameter cost_dat(regions, years,mp,type);
parameter cost_dat_1(years,mp,type);
parameter tons(regions,years,mp,i,t);
parameter tons_t(regions,years,mp,i);
parameter tons_f(regions,years,mp);
parameter tons_r(years,mp);

parameter npvv(regions,mp);


parameter Tranv(regions,years,mp,ip,i,k,t);
parameter Tranv_t(regions,years,mp,ip,i,k);
parameter Tranv_f(regions,years,mp,k);
parameter Tranv_r(years,mp,k);

parameter Bv(regions,years,mp,i,d,z,t);
parameter Bv_t(regions,years,mp,i,d,z);
parameter Bv_f(regions,years,mp,d,z);
parameter Bv_r(years,mp,d,z);

parameter Biv(regions,years,mp,i,d,procset,t);
parameter Biv_t(regions,years,mp,i,d,procset);
```

```
parameter Biv_f(regions,years,mp,d,procset);
parameter Biv_r(years,mp,d,procset);

parameter Nv(regions,years,mp,ip,i,procset,t);
parameter Nv_t(regions,years,mp,ip,i,procset);
parameter Nv_f(regions,years,mp,procset);
parameter Nv_r(years,mp,procset);

parameter deliv(regions,years,mp,procset)


parameter Sv(regions,years,mp,i,k,t);
parameter Sv_t(regions,years,mp,i,k);
parameter Sv_f(regions,years,mp,k);

parameter Siv(regions,years,mp,i,k,z,t);
parameter Siv_t(regions,years,mp,i,k,z);
parameter Siv_f(regions,years,mp,k,z);

model model1 /all/;
loop((regions,mp)$(ord(mp) eq 4),
g(f) = all_sets(f,regions);
maxp = caps(mp);

S.l(i,k,t,sc) = 0;

B.l(i,d,z,t,sc) = 0;
npv.l = 0;
npv.lo = 0;
za.l(i,procset) = 0;
Tran.l(ip,i,k,t,sc) = 0;


 solve model1 using mip maximizing npv;
$Ontext
Sv(regions,years,mp,i,k,t) = S.l(i,k,t,sc);
Sv_t(regions,years,mp,i,k) = sum(t,S.l(i,k,t,sc));
Sv_f(regions,years,mp,k) = sum((i,t), S.l(i,k,t,sc));



miles_term(regions,years,mp,i,t) =
sum((procdo,procset)$B.l(i,procdo,procset,t,sc),B.l(i,procdo,procset,t,
sc)*miles_term1(i)*.1);
miles_term_t(regions,years,mp,i) =
sum((t,procdo,procset)$B.l(i,procdo,procset,t,sc),B.l(i,procdo,procset,
sc)*miles_term1(i)*.1);
miles_term_f(regions,years,mp) =
sum((i,t,procdo,procset)$B.l(i,procdo,procset,t,sc),
B.l(i,procdo,procset,t,sc)*miles_term1(i)*.1);
$Offtext

cost_dat(regions,sc,mp,type) = cost.l(type,sc);

$Ontext
miles_pipe(regions,years,mp,i,t) =
sum((procdo,procset)$B.l(i,procdo,procset,t,sc),B.l(i,procdo,procset,t,
sc)*miles_pipe1(i)*0.0161);
miles_pipe_t(regions,years,mp,i) =
sum((procdo,procset,t)$B.l(i,procdo,procset,t,sc),
B.l(i,procdo,procset,t,sc)*miles_pipe1(i)*0.0161);
miles_pipe_f(regions,years,mp) =
sum((procdo,procset,i,t)$B.l(i,procdo,procset,t,sc),
B.l(i,procdo,procset,t,sc)*miles_pipe1(i)*0.0161);
```

```
miles_unit_num(regions,years,mp,ip,i,procset,t) =
N_tran.l(ip,i,procset,t);
miles_unit_t_num(regions,years,mp,ip,i,procset) =
sum(t$N_tran.l(ip,i,procset,t), N_tran.l(ip,i,procset,t));
miles_unit_f_num(regions,years,mp,procset) =
sum((t,ip,i)$N_tran.l(ip,i,procset,t),N_tran.l(ip,i,procset,t));


miles_unit(regions,years,mp,ip,i,procset,t) =
N_tran.l(ip,i,procset,t)*c_transport1(i,ip)*tran3(procset);
miles_unit_t(regions,years,mp,ip,i,procset) =
sum(t$N_tran.l(ip,i,procset,t),
N_tran.l(ip,i,procset,t)*c_transport1(i,ip)*tran3(procset)*(1/.62));
miles_unit_f(regions,years,mp,procset) =
sum((t,ip,i)$N_tran.l(ip,i,procset,t),N_tran.l(ip,i,procset,t)*c_transp
ort1(i,ip)*tran3(procset)*(1/.62));
$Offtext

B_plant(regions,years,mp,i) = pp.l(i);

npvv(regions,mp) = npv.l;



$Ontext
Tranv(regions,years,mp,ip,i,k,t) = Tran.l(ip,i,k,t,sc);
Tranv_t(regions,years,mp,ip,i,k) = sum(t$Tran.l(ip,i,k,t,sc),
Tran.l(ip,i,k,t,sc));
Tranv_f(regions,years,mp,k) =
sum((t,ip,i)$Tran.l(ip,i,k,t,sc),Tran.l(ip,i,k,t,sc));


Bv(regions,years,mp,i,d,z,t) = B.l(i,d,z,t,sc);
Bv_t(regions,years,mp,i,d,z) = sum(t$B.l(i,d,z,t),B.l(i,d,z,t,sc));
Bv_f(regions,years,mp,d,z) = sum((i,t)$B.l(i,d,z,t), B.l(i,d,z,t,sc));


Biv(regions,years,mp,i,d,procset,t) = Bi.l(i,d,procset,t,sc);
Biv_t(regions,years,mp,i,d,procset) = sum((t)$Bi.l(i,d,procset,t,sc),
Bi.l(i,d,procset,t,sc));
Biv_f(regions,years,mp,d,procset) = sum((i,t)$Bi.l(i,d,procset,t,sc),
Bi.l(i,d,procset,t,sc));
$Offtext

$Ontext
Nv(regions,years,mp,ip,i,procset,t) = N_tran.l(ip,i,procset,t);
Nv_t(regions,years,mp,ip,i,procset) = sum(t$N_tran.l(ip,i,procset,t),
N_tran.l(ip,i,procset,t));
Nv_f(regions,years,mp,procset) = sum((ip,i,t)$N_tran.l(ip,i,procset,t),
N_tran.l(ip,i,procset,t));

$Offtext

deliv(regions,years,mp,procset) = sum(i,za.l(i,procset));

acres(regions,years,mp,i,t) = pp.l(i)*Land(i);
acres_t(regions,years,mp,i) = pp.l(i)*Land(i));
acres_t_1(regions,years,mp,i) = pp.l(i)*Land(i);
acres_f(regions,years,mp) = sum(i,pp.l(i)*Land(i));

parameter npvv_r(mp);
```

```
cost_dat_1(sc,mp,type) = sum(regions, cost_dat(regions,sc,mp,type));

npvv_r(mp) = sum(regions, npvv(regions,mp));
parameter deliv_r(years,mp,procset);
$Ontext
miles_term_r(years,mp) = sum(regions,miles_term_f(regions,years,mp));
miles_pipe_r(years,mp) = sum(regions,miles_pipe_f(regions,years,mp));
miles_unit_r(years,mp,procset) = sum(regions,
miles_unit_f(regions,years,mp,procset));
miles_unit_r_num(years,mp,procset) = sum(regions,
miles_unit_f_num(regions,years,mp,procset));
tons_r(years,mp) = sum(regions, tons_f(regions,years,mp));

Tranv_r(years,mp,k) = sum(regions, Tranv_f(regions,years,mp,k));
Bv_r(years,mp,d,z) = sum(regions, Bv_f(regions,years,mp,d,z));
Biv_r(years,mp,d,procset) = sum(regions,
Biv_f(regions,years,mp,d,procset));
Nv_r(years,mp,procset) = sum(regions, Nv_f(regions,years,mp,procset));
$Offtext
deliv_r(years,mp,procset) = sum(regions,
deliv(regions,years,mp,procset));
B_plant_r(years,mp,i) = sum(regions, B_plant(regions,years,mp,i));
acres_r(years,mp) = sum(regions, acres_f(regions,years,mp));


$ontext
1       Acres
2       Tons
3       Planting & Harvest Costs
4       Variable Processing Costs
5       Processor Med
6       Porcessor Small
7       Capacity
8       ton-miles oil truck
9       ton-miles oil pipeline
10      Cost Oil Truck
11      Cost Oil Pipeline
12      Unit Transport Costs
13      Processor Cost
14      Setup Costs
15      Num Moves Small
16     Num Moves Med
17      Oil Value
18      char
19      gas value
20      NPV

$offtext


file f_cost_dat/cost_dat.csv/;
f_cost_dat.pc = 5;
put f_cost_dat;
loop((regions,sc,mp,type)$cost_dat(regions,sc,mp,type),
put regions.te(regions), sc.te(sc), mp.te(mp),type.te(type),
cost_dat(regions,sc,mp,type)/;
);
putclose;


file f_cost_dat1/cost_dat1.csv/;
f_cost_dat1.pc = 5;
put f_cost_dat1;
```

```
loop((sc,type,mp)$cost_dat_1(sc,mp,type),
put  sc.te(sc), mp.te(mp),type.te(type), cost_dat_1(sc,mp,type)/;
);
putclose;
$Ontext
file f_miles_term_f /miles_term_f.csv/;
f_miles_term_f.pc = 5;
put f_miles_term_f;
loop((regions,years,mp)$miles_term_f(regions,years,mp),
put regions.te(regions),
years.te(years),mp.te(mp),miles_term_f(regions,years,mp)/;
);
putclose;

file f_miles_term_r /miles_term_r.csv/;
f_miles_term_r.pc = 5;
put f_miles_term_r;
loop((years,mp)$miles_term_r(years,mp),
put  years.te(years),mp.te(mp),miles_term_r(years,mp)/;
);
putclose;



file f_miles_pipe /miles_pipe.csv/;
f_miles_pipe.pc = 5;
put f_miles_pipe;
loop((regions,years,mp,i,t)$miles_pipe(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
miles_pipe(regions,years,mp,i,t)/;
);
putclose;

file f_miles_pipe_t /miles_pipe_t.csv/;
f_miles_pipe_t.pc = 5;
put f_miles_pipe_t;
loop((regions,years,mp,i)$miles_pipe_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
miles_pipe_t(regions,years,mp,i)/;
);
putclose;


file f_miles_pipe_f /miles_pipe_f.csv/;
f_miles_pipe_f.pc = 5;
put f_miles_pipe_f;
loop((regions,years,mp)$miles_pipe_f(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),miles_pipe_f(regions,years,mp)/;
);
putclose;

file f_miles_pipe_r /miles_pipe_r.csv/;
f_miles_pipe_r.pc = 5;
put f_miles_pipe_r;
loop((years,mp)$miles_pipe_r(years,mp),
put years.te(years), mp.te(mp),miles_pipe_r(years,mp)/;
);
putclose;


**************************************

file f_miles_unit /miles_unit.csv/;
```

```
f_miles_unit.pc = 5;
put f_miles_unit;
loop((regions,years,mp,ip,i,procset,t)$miles_unit(regions,years,mp,ip,i
,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), procset.te(procset), t.te(t),
miles_unit(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_miles_unit_t /miles_unit_t.csv/;
f_miles_unit_t.pc = 5;
put f_miles_unit_t;
loop((regions,years,mp,ip,i,procset)$miles_unit_t(regions,years,mp,ip,i
,procset),
put  regions.te(regions), years.te(years), ip.te(ip),
i.te(i),mp.te(mp), procset.te(procset),
miles_unit_t(regions,years,mp,ip,i,procset)/;
);
putclose;


file f_miles_unit_f /miles_unit_f.csv/;
f_miles_unit_f.pc = 5;
put f_miles_unit_f;
loop((regions,years,procset,mp)$miles_unit_f(regions,years,mp,procset),
put  regions.te(regions), years.te(years),procset.te(procset),
miles_unit_f(regions,years,mp,procset)/;
);
putclose;

file f_miles_unit_r /miles_unit_r.csv/;
f_miles_unit_r.pc = 5;
put f_miles_unit_r;
loop((years,procset,mp)$miles_unit_r(years,mp,procset),
put years.te(years), mp.te(mp),procset.te(procset),
miles_unit_r(years,mp,procset)/;
);
putclose;
*******************************


file f_miles_unit_num /miles_unit_num.csv/;
f_miles_unit_num.pc = 5;
put f_miles_unit_num;
loop((regions,years,mp,ip,i,procset,t)$miles_unit_num(regions,years,mp,
ip,i,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), procset.te(procset), t.te(t),
miles_unit_num(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_miles_unit_t_num /miles_unit_t_num.csv/;
f_miles_unit_t_num.pc = 5;
put f_miles_unit_t_num;
loop((regions,years,mp,ip,i,procset)$miles_unit_t_num(regions,years,mp,
ip,i,procset),
put  regions.te(regions), years.te(years), ip.te(ip),
i.te(i),mp.te(mp), procset.te(procset),
miles_unit_t_num(regions,years,mp,ip,i,procset)/;
);
putclose;
```

```
file f_miles_unit_f_num /miles_unit_f_num.csv/;
f_miles_unit_f_num.pc = 5;
put f_miles_unit_f_num;
loop((regions,years,procset,mp)$miles_unit_f_num(regions,years,mp,procs
et),
put  regions.te(regions), years.te(years),procset.te(procset),
miles_unit_f_num(regions,years,mp,procset)/;
);
putclose;

file f_miles_unit_r_num /miles_unit_r_num.csv/;
f_miles_unit_r_num.pc = 5;
put f_miles_unit_r_num;
loop((years,procset,mp)$miles_unit_r_num(years,mp,procset),
put years.te(years), mp.te(mp),procset.te(procset),
miles_unit_r_num(years,mp,procset)/;
);
putclose;
*******************************

$Offtext

file f_acres /acres.csv/;
f_acres.pc = 5;
put f_acres;
loop((regions,years,mp,i,t)$acres(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
acres(regions,years,mp,i,t)/;
);
putclose;

file f_acres_t /acres_t.csv/;
f_acres_t.pc = 5;
put f_acres_t;
loop((regions,years,mp,i)$acres_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
acres_t(regions,years,mp,i)/;
);
putclose;


file f_acres_f /acres_f.csv/;
f_acres_f.pc = 5;
put f_acres_f;
loop((regions,years,mp)$acres_f(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),acres_f(regions,years,mp)/;
);
putclose;

file f_acres_r /acres_r.csv/;
f_acres_r.pc = 5;
put f_acres_r;
loop((years,mp)$acres_r(years,mp),
put years.te(years),mp.te(mp), acres_r(years,mp)/;
);
putclose;
*******************************************


file f_npvv /npvv.csv/;
f_npvv.pc = 5;
put f_npvv;
```

```
loop((regions,mp)$npvv(regions,mp),
put  regions.te(regions),  mp.te(mp),npvv(regions,mp)/;
);
putclose;

file f_npvv_r /npvv_r.csv/;
f_npvv_r.pc = 5;
put f_npvv_r;
loop((mp)$npvv_r(mp),
put mp.te(mp), npvv_r(mp)/;
);
putclose;
*******************************
$Ontext
file f_Tranv /Tranv.csv/;
f_Tranv.pc = 5;
put f_Tranv;
loop((regions,years,mp,ip,i,k,t)$Tranv(regions,years,mp,ip,i,k,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), t.te(t), k.te(k), Tranv(regions,years,mp,ip,i,k,t)/;
);
putclose;

file f_Tranv_t /Tranv_t.csv/;
f_Tranv_t.pc = 5;
put f_Tranv_t;
loop((regions,years,mp,ip,i,k)$Tranv_t(regions,years,mp,ip,i,k),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
ip.te(ip),k.te(k),  Tranv_t(regions,years,mp,ip,i,k)/;
);
putclose;


file f_Tranv_f /Tranv_f.csv/;
f_Tranv_f.pc = 5;
put f_Tranv_f;
loop((regions,years,mp,k)$Tranv_f(regions,years,mp,k),
put  regions.te(regions), years.te(years),mp.te(mp),k.te(k),
Tranv_f(regions,years,mp,k)/;
);
putclose;

file f_Tranv_r /Tranv_r.csv/;
f_Tranv_r.pc = 5;
put f_Tranv_r;
loop((years,mp,k)$Tranv_r(years,mp,k),
put years.te(years),mp.te(mp), k.te(k),Tranv_r(years,mp,k)/;
);
putclose;
************************************************************

file f_Bv /Bv.csv/;
f_Bv.pc = 5;
put f_Bv;
loop((regions,years,mp,i,d,z,t)$Bv(regions,years,mp,i,d,z,t),
put  regions.te(regions), years.te(years),mp.te(mp),i.te(i), d.te(d),
z.te(z), t.te(t), Bv(regions,years,mp,i,d,z,t), lat(i), lon(i)/;
);
putclose;

file f_Bv_t /Bv_t.csv/;
f_Bv_t.pc = 5;
put f_Bv_t;
loop((regions,years,mp,i,d,z)$Bv_t(regions,years,mp,i,d,z),
```

```
put  regions.te(regions), years.te(years), mp.te(mp),i.te(i), d.te(d),
z.te(d),  Bv_t(regions,years,mp,i,d,z)/;
);
putclose;


file f_Bv_f /Bv_f.csv/;
f_Bv_f.pc = 5;
put f_Bv_f;
loop((regions,years,mp,d,z)$Bv_f(regions,years,mp,d,z),
put  regions.te(regions), years.te(years),mp.te(mp),d.te(d), z.te(z),
Bv_f(regions,years,mp,d,z)/;
);
putclose;

file f_Bv_r /Bv_r.csv/;
f_Bv_r.pc = 5;
put f_Bv_r;
loop((years,mp,d,z)$Bv_r(years,mp,d,z),
put years.te(years),mp.te(mp), d.te(d), z.te(z), Bv_r(years,mp,d,z)/;
);
putclose;
*****************************************************************

file f_Biv /Biv.csv/;
f_Biv.pc = 5;
put f_Biv;
loop((regions,years,mp,i,procdo,procset,t)$Biv(regions,years,mp,i,procd
o,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
procdo.te(procdo), procset.te(procset), t.te(t),
Biv(regions,years,mp,i,procdo,procset,t)/;
);
putclose;

file f_Biv_t /Biv_t.csv/;
f_Biv_t.pc = 5;
put f_Biv_t;
loop((regions,years,mp,i,procdo,procset)$Biv_t(regions,years,mp,i,procd
o,procset),
put  regions.te(regions), years.te(years), mp.te(mp), i.te(i),
procdo.te(procdo), procset.te(procset),
Biv_t(regions,years,mp,i,procdo,procset)/;
);
putclose;



file f_Biv_f /Biv_f.csv/;
f_Biv_f.pc = 5;
put f_Biv_f;
loop((regions,years,mp,procdo,procset)$Biv_f(regions,years,mp,procdo,pr
ocset),
put  regions.te(regions), years.te(years),mp.te(mp),procdo.te(procdo),
procset.te(procset), Biv_f(regions,years,mp,procdo,procset)/;
);
putclose;

file f_Biv_r /Biv_r.csv/;
f_Biv_r.pc = 5;
put f_Biv_r;
loop((years,mp,procdo,procset)$Biv_r(years,mp,procdo,procset),
put years.te(years), mp.te(mp),procdo.te(procdo), procset.te(procset),
Biv_r(years,mp,procdo,procset)/;
```

```
);
putclose;
************************************************************************
******
file f_Nv /Nv.csv/;
f_Nv.pc = 5;
put f_Nv;
loop((regions,years,mp,ip,i,procset,t)$Nv(regions,years,mp,ip,i,procset
,t),
put  regions.te(regions), years.te(years), mp.te(mp)ip.te(ip), i.te(i),
t.te(t), procset.te(procset), lat(i), lon(i), lat(ip), lon(ip),
Nv(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_Nv_t /Nv_t.csv/;
f_Nv_t.pc = 5;
put f_Nv_t;
loop((regions,years,mp,ip,i,procset)$Nv_t(regions,years,mp,ip,i,procset
),
put  regions.te(regions), years.te(years), mp.te(mp),i.te(i),
ip.te(ip),procset.te(procset),  Nv_t(regions,years,mp,ip,i,procset)/;
);
putclose;


file f_Nv_f /Nv_f.csv/;
f_Nv_f.pc = 5;
put f_Nv_f;
loop((regions,years,mp,procset)$Nv_f(regions,years,mp,procset),
put  regions.te(regions),
mp.te(mp),years.te(years),procset.te(procset),
Nv_f(regions,years,mp,procset)/;
);
putclose;

file f_Nv_r /Nv_r.csv/;
f_Nv_r.pc = 5;
put f_Nv_r;
loop((years,mp,procset)$Nv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),Nv_r(years,mp,procset)/;
);
putclose;
************************************************************************
******
$Offtext

file f_deliv /deliv.csv/;
f_deliv.pc = 5;
put f_deliv;
loop((regions,years,mp,procset)$deliv(regions,years,mp,procset),
put  regions.te(regions),
years.te(years),mp.te(mp),procset.te(procset),
deliv(regions,years,mp,procset)/;
);
putclose;

file f_deliv_r /deliv_r.csv/;
f_deliv_r.pc = 5;
put f_deliv_r;
loop((years,mp,procset)$deliv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),deliv_r(years,mp,procset)/;
```

```
);
putclose;
```

Mobile Processing Code: Stochastic

```
$TITLE Optimal Design for Biomass Processing and Distribution Network


set i /
$include setreal.inc
/;
alias(i,ip);
set t
/1*14/;

alias(t,tp);
set r
/farm, refinery,terminal/;

set d tasks
/
plant
harvest
proc
wait

tran_come

/;
alias(d,dp);
set k resources
/
planted
harvested
oil_gal
coming
going
ready
char_ton
MMBTU
clean
dirty
switch_small
switch_med
final_oil
/;

set k3(k)
/
oil_gal
char_ton
MMBTU
final_oil
/;
set make_k(k)
/
switch_small
switch_med
/;

set z size
/
switch
small
med
```

```
/;

set p
/
b
a
/;

alias(i,ip);
*alias(t,tp);









set real_arcs(ip,i)
/
$include real_arcs.inc
/;



parameter c_transport1(ip,i)
/
$include cost_100max.inc
/;



parameter central_cost(i)
/
$include terminal_final.inc
/;

parameter pipeline_cost(i)
/
$include pipeline_cost.inc
/;

set f(i)
/
$include set_real2.inc
/;

set l(i)
/
PASCAGOULA_30
/;

set regions
/
$include terminal_set.inc
/;

parameter region_name(i)
/
$include region_name.inc
/;
```

```
scalar region_live;


region_live = 1;


set term_seti
/
$include term_set.inc
/;

set years/1978*2052/;

alias(years,yp);

set sc(yp)
/
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
/;


parameter all_yields(i,years)
/
$include all_yields.inc
/;

set g(f);

set all_sets(f,regions)
/
$include all_sets.inc
/;

g(f) = all_sets(f,'211_79');


alias(g,gp);



parameter yielda(f)
/
$include yielda1983.inc
/;

parameter region_rank(regions)
/
206_86 1
218_89 2
203_90 3
232_92 4
243_93 5
248_105 6
211_79 7
```

```
/;
parameter yieldb(f)
/
$include avgyieldreal.inc
/;

parameter yieldc(f)
/
$include yielda2005.inc
/;

parameter Land(i)
/
$include landreal.inc
/;


set procset(z)
/
small
med
/;

set procdo(d)
/
proc
tran_come
/;
parameter lat(i)
/
$include lat.inc
/;
parameter lon(i)
/
$include lon.inc
/;



set term(i)
/
$include terminal_set.inc
/;


set term_set(i,ip)
/
$include terminal_set1.inc
/;


Variables
npv;

positive variables
S(i,k,t,sc)
S1(i,k)
S2(k,t)
De(k,t)
B(i,d,z,t,sc)
pp(i)
Tran(ip,i,k,t,sc)

po
```

```
B_tran(k,t)
Deli2(i,k)
S2(k,t)
extra(i,procdo,procset,t)
B1(i,d,z,t);

integer variables
Si(i,k,z,t,sc)
move(i,dp,d,z,t)
moves(procset)
Bi(i,d,z,t,sc)
Deli(procset,sc)

E(f)


Si1(i,k,d,z,t)
Sid(i,k,d,z,t)
N_tran(ip,i,z,t,sc);


Equations
*planted(f,t)







*demand


proc1(i, procset,t,sc)
proc2(i,procset,t,sc)









*eff(fp,f,t)

har3(i,t,sc)
har1(i,t,sc)

oil1(i,t,sc)
oil2(i,t,sc)
units1(procset,sc)
units2(i,procset,t,sc)
planted1(i,t,sc)
planted2(i,t,sc)
planted3(i,t,sc)

units22(i,procset,t,sc)
planted4(i,t,sc)
processed3(i,t,sc)

costy
plea(i)
proc7(i,procset,t,sc)
proc8(i,procset,t,sc)
```

```
;
****************************
set mp /1*5/;
scalar maxp;

parameter caps(mp)
/
1 0.01
2 0.02
3 0.05
4 0.1
5 0.2
/;
parameter acres1(i)
/
$include acres1.inc
/;
maxp = caps('4');
deli.up('small',sc) = 5000;
deli.up('med',sc) = 5000;
alias(i,ip);

parameter beta(t);

beta('1') = 0.95;
beta('2') = 1.0;
beta('3') = 0.95;

set costout /1*20/;
plea(g) .. pp(g) =l= 0.1;
planted1(g,t,sc)$((ord(t) eq 1)  ) .. B(g,'harvest','switch',t,sc) =l=
pp(g);
planted2(g,t,sc)$(ord(t) eq 2   ) ..  B(g,'harvest','switch',t,sc) +
B(g,'harvest','switch',t-1,sc) =l= pp(g);
planted3(g,t,sc)$(ord(t) eq 3  ) ..  B(g,'harvest','switch',t,sc) +
B(g,'harvest','switch',t-1,sc) + B(g,'harvest','switch',t-2,sc) =l=
pp(g);
planted4(g,t,sc)$(ord(t) ge 4 )  ..  B(g,'harvest','switch',t,sc)  =e=
0;

parameter cnvt(k3)
/
oil_gal 135
char_ton .28
MMBTU 17.55
/;

parameter cvtf(k3)
/
oil_gal 1
char_ton 0.002074
MMBTU .13
/;
parameter arc_pay2(f)
/
$include arc_pay2.inc
/;

har3(g,t,sc)$(ord(t) ge 2)   .. S(g,'harvested',t,sc) =e=
(S(g,'harvested',t-1,sc)*.99125) + (B(g,'harvest','switch',t-
1,sc)*beta(t-1)*all_yields(g,sc))*0.446*Land(g) -
sum((procdo,procset),B(g,procdo,procset,t,sc));
```

```
har1(g,t,sc)$(ord(t) eq 1 )  .. S(g,'harvested',t,sc)  =e=  0 -
sum((procdo,procset),B(g,procdo,procset,t,sc));



oil1(g,t,sc)$((ord(t) eq 1)   ) .. S(g,'final_oil',t,sc) =e=  0 -
sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t,sc)) + sum(gp$(term_set(gp,g) and
(not term(gp)) and (term(g))),Tran(gp,g,'final_oil',t,sc)) -
Tran(g,'PASCAGOULA_30','final_oil',t,sc)$term(g);
oil2(g,t,sc)$((ord(t) ge 2)    ) .. S(g,'final_oil',t,sc) =e=
S(g,'final_oil',t-1,sc) + sum((procdo,procset),B(g,procdo,procset,t-
1,sc)*.8)- sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t,sc)) + sum(gp$(term_set(gp,g) and
(not term(gp)) and (term(g))),Tran(gp,g,'final_oil',t,sc)) -
Tran(g,'PASCAGOULA_30','final_oil',t,sc)$term(g) ;



processed3(i,t,sc)$(l(i) ) .. S(i,'final_oil',t,sc) =e=
S(i,'final_oil',t-1,sc)$(ord(t) ge 2) +
sum((g)$(term(g)),Tran(g,i,'final_oil',t,sc));





parameter maxoo(procset);

maxoo('med') = 3000;
maxoo('small') = 3000*.5;

units1(procset,sc) .. Sum(g,Si(g,'clean',procset,'1',sc))  =e=
Deli(procset,sc);




units2(g,procset,t,sc)$(ord(t) ge 2) .. Si(g,'clean',procset,t,sc) =e=
Si(g,'clean',procset,t-1,sc)  +
sum(gp$(real_arcs(gp,g)),N_tran(gp,g,procset,t,sc)) +
Bi(g,'wait',procset,t,sc)  - Bi(g,'tran_come',procset,t,sc);
units22(g,procset,t,sc)$(ord(t) ge 2) .. Bi(g,'tran_come',procset,t-
1,sc)$(ord(t) ge 3)  - sum(gp$(real_arcs(g,gp)
),N_tran(g,gp,procset,t,sc)) + Bi(g,'proc',procset,t-1,sc)$(ord(t) ge
3) - Bi(g,'proc',procset,t,sc) - Bi(g,'wait',procset,t,sc) =e= 0;








parameter maxdo(procset);

maxdo('med') = 1;
maxdo('small') = 0.5;

parameter tran_max(procset)
/
small 1100
med 2200
/;
```

```
parameter arc_cap(i,ip)
/
$include arc_cap.inc
/;




proc1(g, procset,t,sc) .. B(g,'proc',procset,t,sc) =l=
Bi(g,'proc',procset,t,sc)*maxdo(procset)*3000  ;
proc2(g, procset,t,sc) .. B(g,'proc',procset,t,sc) =g=
Bi(g,'proc',procset,t,sc)*maxdo(procset)*3000*.1;


proc7(g,procset,t,sc) .. B(g,'tran_come',procset,t,sc) =l=
Bi(g,'tran_come',procset,t,sc)*maxdo(procset)*2600;
proc8(g,procset,t,sc) .. B(g,'tran_come',procset,t,sc) =g=
Bi(g,'tran_come',procset,t,sc)*maxdo(procset)*2600*.1;
parameter terminal_b(f)
/
$include terminal_b.inc
/;

parameter procvar(procset)
/
med 164
small 108
/;

parameter procfix(procset)
/
med 21000
small 10500
/;

parameter costset(procset)
/
med 76000
small 50000
/;

parameter costbig(procset)
/
med 131000
small 87000
/;

parameter costtran(procset)
/
med 3
small 2
/;

set doplant(d)
/
plant
harvest
/;

parameter costdoplant(doplant)
/
plant 434
harvest 275
```

```
/;


parameter cost1(k)
/
harvested 434
final_oil 870000
/;

parameter chold(k)
/
harvested 0.03
/;
$ontext
parameter mmbtu_value(f,l)
/
$include mmbtu_val.inc
/;
$offtext
parameter procy(procset)
/
small 7700
med 15400
/;

parameter fix(procset)
/
small 424
med 528
/;

parameter fix1(procset)
/
small 1271000
med 1583000
/;

parameter tran3(procset)
/
small 2
med 3
/;

parameter cost_ref(i)
/
$include cost_ref.inc
/;

parameter cost_term(ip,i)
/
$include cost_term.inc
/;

parameter cost_ref1(i)
/
$include cost_ref1.inc
/;

parameter cost_term1(i)
/
$include terminal_cost.inc
/;

parameter miles_pipe1(i);
```

```
set kdo(k)
/
coming
going
/;

miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');


set type
/
oil_val
variable_proc
fix_tran
unit_cost
char_val
oil_tran_term
oil_tran_truck
plant_cost
variable_tran
/;

set type2(type)
/
oil_val
variable_proc
fix_tran
unit_cost
char_val
oil_tran_term
oil_tran_truck
variable_tran/;

variable cost(type,sc);

equations
cost11(sc)
cost2(sc)
cost3(sc)
cost4(sc)
cost5(sc)
cost6(sc)
cost7(sc)
cost8(sc)
cost9(sc);

cost11(sc) .. cost('oil_val',sc) =e=
sum(l,S(l,'final_oil','14',sc))*241.8;
cost2(sc) .. cost('variable_proc',sc) =e= -1*sum((g,procset,procdo,t),
B(g,procdo,procset,t,sc))*8.61;

cost5(sc) .. cost('char_val',sc) =e= 6*sum((g,procset,procdo,t),
B(g,procdo,procset,t,sc));


cost3(sc) .. cost('fix_tran',sc) =e= -
```

```
1*sum((real_arcs(g,gp),procset,t),N_tran(gp,g,procset,t,sc)*fix(procset
)) - sum((g,procset,t),Bi(g,'wait',procset,t,sc)*fix(procset));

cost4(sc) .. cost('unit_cost',sc) =e= -1*sum((procset),
Deli(procset,sc)*fix1(procset));

cost6(sc) .. cost('oil_tran_term',sc) =e= -
1*sum((g,l,t)$(term(g)),Tran(g,l,'final_oil',t,sc)*pipeline_cost(g)*0.0
161);

cost7(sc) .. cost('oil_tran_truck',sc) =e= -
1*sum((g,gp,t)$((term_set(g,gp) and
term(gp))),Tran(g,gp,'final_oil',t,sc)*cost_term1(g)*.1);
cost8(sc) .. cost('plant_cost',sc) =e= -1*sum((g),pp(g)*Land(g))*322;

cost9(sc) .. cost('variable_tran',sc) =e= -
1*sum((real_arcs(g,gp),procset,t),N_tran(gp,g,procset,t,sc)*(
tran3(procset)*(1/.62)*c_transport1(g,gp)));

costy .. npv =e= -1*sum(g,pp(g)*Land(g))*322 + .1*sum((type2,sc),
cost(type2,sc));









option lp = cplex;
option mip = cplex;



parameter miles_pipe1(i);
miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');
parameter miles_term1(i)
/
$include terminal_cost.inc
/;

parameter B_plant(regions,years,mp,i);
parameter B_plant_r(years,mp,i);
parameter miles_term(regions,years,mp,i,t);
parameter miles_term_t(regions,years,mp,i);
parameter miles_term_f(regions,years,mp);


parameter miles_pipe(regions,years,mp,i,t);
parameter miles_pipe_t(regions,years,mp,i);
parameter miles_pipe_f(regions,years,mp);


parameter miles_unit(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t(regions,years,mp,ip,i,procset);
parameter miles_unit_f(regions,years,mp,procset);
```

```
parameter miles_unit_r(years,mp,procset);

parameter miles_unit_num(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t_num(regions,years,mp,ip,i,procset);
parameter miles_unit_f_num(regions,years,mp,procset);
parameter miles_unit_r_num(years,mp,procset);


parameter acres(regions,years,mp,i,t);
parameter acres_t_1(regions,years,mp,i);
parameter acres_t(regions,years,mp,i);
parameter acres_f(regions,years,mp);
parameter acres_r(years,mp);
parameter cost_dat(regions, years,type);
parameter cost_dat_1(years,type);
parameter tons(regions,years,mp,i,t);
parameter tons_t(regions,years,mp,i);
parameter tons_f(regions,years,mp);
parameter tons_r(years,mp);

parameter npvv(regions,mp);


parameter Tranv(regions,years,mp,ip,i,k,t);
parameter Tranv_t(regions,years,mp,ip,i,k);
parameter Tranv_f(regions,years,mp,k);
parameter Tranv_r(years,mp,k);

parameter Bv(regions,years,mp,i,d,z,t);
parameter Bv_t(regions,years,mp,i,d,z);
parameter Bv_f(regions,years,mp,d,z);
parameter Bv_r(years,mp,d,z);

parameter Biv(regions,years,mp,i,d,procset,t);
parameter Biv_t(regions,years,mp,i,d,procset);
parameter Biv_f(regions,years,mp,d,procset);
parameter Biv_r(years,mp,d,procset);

parameter Nv(regions,years,mp,ip,i,procset,t);
parameter Nv_t(regions,years,mp,ip,i,procset);
parameter Nv_f(regions,years,mp,procset);
parameter Nv_r(years,mp,procset);
parameter npv_final(regions);
parameter deliv(regions,years,mp,procset)


parameter Sv(regions,years,mp,i,k,t);
parameter Sv_t(regions,years,mp,i,k);
parameter Sv_f(regions,years,mp,k);

parameter Siv(regions,years,mp,i,k,z,t);
parameter Siv_t(regions,years,mp,i,k,z);
parameter Siv_f(regions,years,mp,k,z);

model model1 /all/;
loop((regions,mp)$((ord(mp) eq 4) ),
g(f) = all_sets(f,regions);
maxp = caps(mp);

S.l(i,k,t,sc) = 0;
Si.l(i,k,z,t,sc) = 0;
B.l(i,d,z,t,sc) = 0;
npv.l = 0;
deli.l(procset,sc) = 0;
```

```
Bi.l(i,d,z,t,sc) = 0;
Tran.l(ip,i,k,t,sc) = 0;
N_tran.l(ip,i,z,t,sc) = 0;

 solve model1 using mip maximizing npv;

Sv(regions,sc,mp,i,k,t) = S.l(i,k,t,sc);
Sv_t(regions,sc,mp,i,k) = sum((t),S.l(i,k,t,sc));
Sv_f(regions,sc,mp,k) = sum((i,t), S.l(i,k,t,sc));

Siv(regions,sc,mp,i,k,z,t) = Si.l(i,k,z,t,sc);
Siv_t(regions,sc,mp,i,k,z) = sum((t),Si.l(i,k,z,t,sc));
Siv_f(regions,sc,mp,k,z) = sum((i,t), Si.l(i,k,z,t,sc));
npv_final(regions) = npv.l;
miles_term(regions,sc,mp,i,t) =
sum((procdo,procset)$B.l(i,procdo,procset,t,sc),B.l(i,procdo,procset,t,
sc)*miles_term1(i)*.1);
miles_term_t(regions,sc,mp,i) =
sum((t,procdo,procset)$B.l(i,procdo,procset,t,sc),B.l(i,procdo,procset,
t,sc)*miles_term1(i)*.1);
miles_term_f(regions,sc,mp) =
sum((i,t,procdo,procset)$B.l(i,procdo,procset,t,sc),
B.l(i,procdo,procset,t,sc)*miles_term1(i)*.1);

cost_dat(regions,sc,type) = cost.l(type,sc);

miles_pipe(regions,sc,mp,i,t) =
sum((procdo,procset)$B.l(i,procdo,procset,t,sc),B.l(i,procdo,procset,t,
sc)*miles_pipe1(i)*0.0161);
miles_pipe_t(regions,sc,mp,i) =
sum((procdo,procset,t)$B.l(i,procdo,procset,t,sc),
B.l(i,procdo,procset,t,sc)*miles_pipe1(i)*0.0161);
miles_pipe_f(regions,sc,mp) =
sum((procdo,procset,i,t)$B.l(i,procdo,procset,t,sc),
B.l(i,procdo,procset,t,sc)*miles_pipe1(i)*0.0161);


miles_unit_num(regions,sc,mp,ip,i,procset,t) =
N_tran.l(ip,i,procset,t,sc);
miles_unit_t_num(regions,sc,mp,ip,i,procset) =
sum((t)$N_tran.l(ip,i,procset,t,sc), N_tran.l(ip,i,procset,t,sc));
miles_unit_f_num(regions,sc,mp,procset) =
sum((t,ip,i)$N_tran.l(ip,i,procset,t,sc),N_tran.l(ip,i,procset,t,sc));

miles_unit(regions,sc,mp,ip,i,procset,t) =
N_tran.l(ip,i,procset,t,sc)*c_transport1(i,ip)*tran3(procset);
miles_unit_t(regions,sc,mp,ip,i,procset) =
sum((t)$N_tran.l(ip,i,procset,t,sc),
N_tran.l(ip,i,procset,t,sc)*c_transport1(i,ip)*tran3(procset)*(1/.62));
miles_unit_f(regions,sc,mp,procset) =
sum((t,ip,i)$N_tran.l(ip,i,procset,t,sc),N_tran.l(ip,i,procset,t,sc)*c_
transport1(i,ip)*tran3(procset)*(1/.62));


B_plant(regions,sc,mp,i) = pp.l(i);

npvv(regions,mp) = npv.l;




Tranv(regions,sc,mp,ip,i,k,t) = Tran.l(ip,i,k,t,sc);
Tranv_t(regions,sc,mp,ip,i,k) = sum((t)$Tran.l(ip,i,k,t,sc),
Tran.l(ip,i,k,t,sc));
```

```
Tranv_f(regions,sc,mp,k) =
sum((t,ip,i)$Tran.l(ip,i,k,t,sc),Tran.l(ip,i,k,t,sc));


Bv(regions,sc,mp,i,d,z,t) = B.l(i,d,z,t,sc);
Bv_t(regions,sc,mp,i,d,z) = sum((t)$B.l(i,d,z,t,sc),B.l(i,d,z,t,sc));
Bv_f(regions,sc,mp,d,z) = sum((i,t)$B.l(i,d,z,t,sc), B.l(i,d,z,t,sc));


Biv(regions,sc,mp,i,d,procset,t) = Bi.l(i,d,procset,t,sc);
Biv_t(regions,sc,mp,i,d,procset) = sum((t)$Bi.l(i,d,procset,t,sc),
Bi.l(i,d,procset,t,sc));
Biv_f(regions,sc,mp,d,procset) = sum((i,t)$Bi.l(i,d,procset,t,sc),
Bi.l(i,d,procset,t,sc));



Nv(regions,sc,mp,ip,i,procset,t) = N_tran.l(ip,i,procset,t,sc);
Nv_t(regions,sc,mp,ip,i,procset) = sum((t)$N_tran.l(ip,i,procset,t,sc),
N_tran.l(ip,i,procset,t,sc));
Nv_f(regions,sc,mp,procset) = sum((ip,i,t)$N_tran.l(ip,i,procset,t,sc),
N_tran.l(ip,i,procset,t,sc));


deliv(regions,sc,mp,procset) = deli.l(procset,sc);
acres(regions,sc,mp,i,t) = B.l(i,'plant','switch',t,sc)*Land(i);
acres_t(regions,sc,mp,i) =
sum((t)$B.l(i,'plant','switch',t,sc),B.l(i,'plant','switch',t,sc)*Land(
i));
acres_t_1(regions,sc,mp,i) =
sum((t)$B.l(i,'plant','switch',t,sc),B.l(i,'plant','switch',t,sc)*Land(
i));
acres_f(regions,sc,mp) = sum((i,t)$B.l(i,'plant','switch',t,sc),
B.l(i,'plant','switch',t,sc)*Land(i));

tons(regions,sc,mp,i,t) =
B.l(i,'harvest','switch',t,sc)*Land(i)*all_yields(i,sc);
tons_t(regions,sc,mp,i) =
sum((t)$B.l(i,'harvest','switch',t,sc),B.l(i,'harvest','switch',t,sc)*L
and(i)*all_yields(i,sc));
tons_f(regions,sc,mp) = sum((i,t)$B.l(i,'harvest','switch',t,sc),
B.l(i,'harvest','switch',t,sc)*Land(i)*all_yields(i,sc));
);

parameter npvv_r(years,mp);
parameter miles_pipe_r(years,mp);
parameter miles_term_r(years,mp);
miles_pipe_r(years,mp) = sum(regions, miles_pipe_f(regions,years,mp));
miles_term_r(years,mp) = sum(regions,miles_term_f(regions,years,mp));
cost_dat_1(years,type) = sum(regions, cost_dat(regions,years,type));
parameter deliv_r(years,mp,procset);
miles_term_r(years,mp) = sum(regions,miles_term_f(regions,years,mp));
miles_pipe_r(years,mp) = sum(regions,miles_pipe_f(regions,years,mp));
miles_unit_r(years,mp,procset) = sum(regions,
miles_unit_f(regions,years,mp,procset));
miles_unit_r_num(years,mp,procset) = sum(regions,
miles_unit_f_num(regions,years,mp,procset));
tons_r(years,mp) = sum(regions, tons_f(regions,years,mp));
npvv_r(years,mp) = sum(regions, npvv(regions,mp));
Tranv_r(years,mp,k) = sum(regions, Tranv_f(regions,years,mp,k));
Bv_r(years,mp,d,z) = sum(regions, Bv_f(regions,years,mp,d,z));
Biv_r(years,mp,d,procset) = sum(regions,
Biv_f(regions,years,mp,d,procset));
Nv_r(years,mp,procset) = sum(regions, Nv_f(regions,years,mp,procset));
```

```
deliv_r(years,mp,procset) = sum((regions),
deliv(regions,years,mp,procset));
B_plant_r(years,mp,i) = sum(regions, B_plant(regions,years,mp,i));
acres_r(years,mp) = sum(regions, acres_f(regions,years,mp));


$ontext
1       Acres
2       Tons
3       Planting & Harvest Costs
4       Variable Processing Costs
5       Processor Med
6       Porcessor Small
7       Capacity
8       ton-miles oil truck
9       ton-miles oil pipeline
10      Cost Oil Truck
11      Cost Oil Pipeline
12      Unit Transport Costs
13      Processor Cost
14      Setup Costs
15      Num Moves Small
16     Num Moves Med
17      Oil Value
18      char
19      gas value
20      NPV

$offtext



parameter cost22(costout,years,mp);
cost22('1',years,mp) = acres_r(years,mp);
cost22('2',years,mp) = tons_r(years,mp);
cost22('3',years,mp) = acres_r(years,mp)*322;
cost22('4',years,mp) = sum((procdo,procset),
Bv_r(years,mp,procdo,procset))*15.57;
cost22('5',years,mp) = deliv_r(years,mp,'small');
cost22('6',years,mp) = deliv_r(years,mp,'med');
cost22('7',years,mp) = deliv_r(years,mp,'small')*1500*12 +
deliv_r(years,mp,'med')*3000*12;
cost22('8',years,mp) = miles_pipe_r(years,mp)*(1/0.0161);
cost22('9',years,mp) = miles_term_r(years,mp)*(1/0.1);
cost22('10',years,mp) = miles_pipe_r(years,mp);
cost22('11',years,mp) = 700;
cost22('12',years,mp) = miles_term_r(years,mp);
cost22('13',years,mp) = sum(procset,miles_unit_r(years,mp,procset));
cost22('14',years,mp) = sum(procset,miles_unit_r(years,mp,procset)) +
sum(procset,Biv_r(years,mp,'wait',procset)*fix(procset));
cost22('15',years,mp) = miles_unit_r_num(years,mp,'small');
cost22('16',years,mp) = miles_unit_r_num(years,mp,'med');
cost22('17',years,mp) = tons_r(years,mp)*.8*241.8;
cost22('18',years,mp) = tons_r(years,mp)*.1*.40;
cost22('19',years,mp) = tons_r(years,mp)*.1*20;
cost22('20',years,mp) = npvv_r(years,mp);

file f_cost_22 /cost_2.csv/;
f_cost_22.pc = 5;
put f_cost_22;
loop((costout,years,mp)$cost22(costout,years,mp),
put costout.te(costout), years.te(years),
mp.te(mp),cost22(costout,years,mp) /;
);
```

```
file f_miles_term /miles_term.csv/;
f_miles_term.pc = 5;
put f_miles_term;
loop((regions,years,mp,i,t)$miles_term(regions,years,mp,i,t),
put regions.te(regions), years.te(years), mp.te(mp), i.te(i), t.te(t),
miles_term(regions,years,mp,i,t) /;
);
putclose;

file f_miles_term_t /miles_term_t.csv/;
f_miles_term_t.pc = 5;
put f_miles_term_t;
loop((regions,years,mp,i)$miles_term_t(regions,years,mp,i),
put regions.te(regions), years.te(years),mp.te(mp), i.te(i),
miles_term_t(regions,years,mp,i)/;
);
putclose;

file f_cost_dat/cost_dat.csv/;
f_cost_dat.pc = 5;
put f_cost_dat;
loop((regions,years,type)$cost_dat(regions,years,type),
put regions.te(regions), years.te(years), type.te(type),
cost_dat(regions,years,type)/;
);
putclose;


file f_cost_dat1/cost_dat1.csv/;
f_cost_dat1.pc = 5;
put f_cost_dat1;
loop((years,type)$cost_dat_1(years,type),
put  years.te(years),type.te(type), cost_dat_1(years,type)/;
);
putclose;

parameter final_money;
final_money = sum((regions),npv_final(regions));

file f_finalmoney/final_money.csv/;
f_finalmoney.pc = 5;
put f_finalmoney;
put final_money/;

file f_miles_term_f /miles_term_f.csv/;
f_miles_term_f.pc = 5;
put f_miles_term_f;
loop((regions,years,mp)$miles_term_f(regions,years,mp),
put regions.te(regions),
years.te(years),mp.te(mp),miles_term_f(regions,years,mp)/;
);
putclose;

file f_miles_term_r /miles_term_r.csv/;
f_miles_term_r.pc = 5;
put f_miles_term_r;
loop((years,mp)$miles_term_r(years,mp),
put  years.te(years),mp.te(mp),miles_term_r(years,mp)/;
);
putclose;
```

```
file f_miles_pipe /miles_pipe.csv/;
f_miles_pipe.pc = 5;
put f_miles_pipe;
loop((regions,years,mp,i,t)$miles_pipe(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
miles_pipe(regions,years,mp,i,t)/;
);
putclose;

file f_miles_pipe_t /miles_pipe_t.csv/;
f_miles_pipe_t.pc = 5;
put f_miles_pipe_t;
loop((regions,years,mp,i)$miles_pipe_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
miles_pipe_t(regions,years,mp,i)/;
);
putclose;


file f_miles_pipe_f /miles_pipe_f.csv/;
f_miles_pipe_f.pc = 5;
put f_miles_pipe_f;
loop((regions,years,mp)$miles_pipe_f(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),miles_pipe_f(regions,years,mp)/;
);
putclose;

file f_miles_pipe_r /miles_pipe_r.csv/;
f_miles_pipe_r.pc = 5;
put f_miles_pipe_r;
loop((years,mp)$miles_pipe_r(years,mp),
put years.te(years), mp.te(mp),miles_pipe_r(years,mp)/;
);
putclose;


**************************************

file f_miles_unit /miles_unit.csv/;
f_miles_unit.pc = 5;
put f_miles_unit;
loop((regions,years,mp,ip,i,procset,t)$miles_unit(regions,years,mp,ip,i
,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), procset.te(procset), t.te(t),
miles_unit(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_miles_unit_t /miles_unit_t.csv/;
f_miles_unit_t.pc = 5;
put f_miles_unit_t;
loop((regions,years,mp,ip,i,procset)$miles_unit_t(regions,years,mp,ip,i
,procset),
put  regions.te(regions), years.te(years), ip.te(ip),
i.te(i),mp.te(mp), procset.te(procset),
miles_unit_t(regions,years,mp,ip,i,procset)/;
);
putclose;
```

```
file f_miles_unit_f /miles_unit_f.csv/;
f_miles_unit_f.pc = 5;
put f_miles_unit_f;
loop((regions,years,procset,mp)$miles_unit_f(regions,years,mp,procset),
put  regions.te(regions), years.te(years),procset.te(procset),
miles_unit_f(regions,years,mp,procset)/;
);
putclose;

file f_miles_unit_r /miles_unit_r.csv/;
f_miles_unit_r.pc = 5;
put f_miles_unit_r;
loop((years,procset,mp)$miles_unit_r(years,mp,procset),
put years.te(years), mp.te(mp),procset.te(procset),
miles_unit_r(years,mp,procset)/;
);
putclose;
*******************************


file f_miles_unit_num /miles_unit_num.csv/;
f_miles_unit_num.pc = 5;
put f_miles_unit_num;
loop((regions,years,mp,ip,i,procset,t)$miles_unit_num(regions,years,mp,
ip,i,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), procset.te(procset), t.te(t),
miles_unit_num(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_miles_unit_t_num /miles_unit_t_num.csv/;
f_miles_unit_t_num.pc = 5;
put f_miles_unit_t_num;
loop((regions,years,mp,ip,i,procset)$miles_unit_t_num(regions,years,mp,
ip,i,procset),
put  regions.te(regions), years.te(years), ip.te(ip),
i.te(i),mp.te(mp), procset.te(procset),
miles_unit_t_num(regions,years,mp,ip,i,procset)/;
);
putclose;


file f_miles_unit_f_num /miles_unit_f_num.csv/;
f_miles_unit_f_num.pc = 5;
put f_miles_unit_f_num;
loop((regions,years,procset,mp)$miles_unit_f_num(regions,years,mp,procs
et),
put  regions.te(regions), years.te(years),procset.te(procset),
miles_unit_f_num(regions,years,mp,procset)/;
);
putclose;

file f_miles_unit_r_num /miles_unit_r_num.csv/;
f_miles_unit_r_num.pc = 5;
put f_miles_unit_r_num;
loop((years,procset,mp)$miles_unit_r_num(years,mp,procset),
put years.te(years), mp.te(mp),procset.te(procset),
miles_unit_r_num(years,mp,procset)/;
);
putclose;
*******************************
```

```
file f_acres /acres.csv/;
f_acres.pc = 5;
put f_acres;
loop((regions,years,mp,i,t)$acres(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
acres(regions,years,mp,i,t)/;
);
putclose;

file f_acres_t /acres_t.csv/;
f_acres_t.pc = 5;
put f_acres_t;
loop((regions,years,mp,i)$acres_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
acres_t(regions,years,mp,i)/;
);
putclose;


file f_acres_f /acres_f.csv/;
f_acres_f.pc = 5;
put f_acres_f;
loop((regions,years,mp)$acres_f(regions,years,mp),
put  regions.te(regions), years.te(years),
mp.te(mp),acres_f(regions,years,mp)/;
);
putclose;

file f_acres_r /acres_r.csv/;
f_acres_r.pc = 5;
put f_acres_r;
loop((years,mp)$acres_r(years,mp),
put years.te(years),mp.te(mp), acres_r(years,mp)/;
);
putclose;
*******************************************


file f_tons /tons.csv/;
f_tons.pc = 5;
put f_tons;
loop((regions,years,mp,i,t)$tons(regions,years,mp,i,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i), t.te(t),
tons(regions,years,mp,i,t)/;
);
putclose;

file f_tons_t /tons_t.csv/;
f_tons_t.pc = 5;
put f_tons_t;
loop((regions,years,mp,i)$tons_t(regions,years,mp,i),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
tons_t(regions,years,mp,i)/;
);
putclose;


file f_tons_f /tons_f.csv/;
f_tons_f.pc = 5;
put f_tons_f;
loop((regions,years,mp)$tons_f(regions,years,mp),
put  regions.te(regions), years.te(years),mp.te(mp),
tons_f(regions,years,mp)/;
);
```

```
putclose;

file f_tons_r /tons_r.csv/;
f_tons_r.pc = 5;
put f_tons_r;
loop((years,mp)$tons_r(years,mp),
put years.te(years),mp.te(mp), tons_r(years,mp)/;
);
putclose;
***************************************************


file f_npvv /npvv.csv/;
f_npvv.pc = 5;
put f_npvv;
loop((regions,mp)$npvv(regions,mp),
put  regions.te(regions), mp.te(mp),npvv(regions,mp)/;
);
putclose;

file f_npvv_r /npvv_r.csv/;
f_npvv_r.pc = 5;
put f_npvv_r;
loop((years,mp)$npvv_r(years,mp),
put years.te(years),mp.te(mp), npvv_r(years,mp)/;
);
putclose;
********************************

file f_Tranv /Tranv.csv/;
f_Tranv.pc = 5;
put f_Tranv;
loop((regions,years,mp,ip,i,k,t)$Tranv(regions,years,mp,ip,i,k,t),
put  regions.te(regions), years.te(years),mp.te(mp), ip.te(ip),
i.te(i), t.te(t), k.te(k),Tranv(regions,years,mp,ip,i,k,t)/;
);
putclose;

file f_Tranv_t /Tranv_t.csv/;
f_Tranv_t.pc = 5;
put f_Tranv_t;
loop((regions,years,mp,ip,i,k)$Tranv_t(regions,years,mp,ip,i,k),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
ip.te(ip),k.te(k),  Tranv_t(regions,years,mp,ip,i,k)/;
);
putclose;


file f_Tranv_f /Tranv_f.csv/;
f_Tranv_f.pc = 5;
put f_Tranv_f;
loop((regions,years,mp,k)$Tranv_f(regions,years,mp,k),
put  regions.te(regions), years.te(years),mp.te(mp),k.te(k),
Tranv_f(regions,years,mp,k)/;
);
putclose;

file f_Tranv_r /Tranv_r.csv/;
f_Tranv_r.pc = 5;
put f_Tranv_r;
loop((years,mp,k)$Tranv_r(years,mp,k),
put years.te(years),mp.te(mp), k.te(k),Tranv_r(years,mp,k)/;
);
putclose;
```

```
*************************************************************

file f_Bv /Bv.csv/;
f_Bv.pc = 5;
put f_Bv;
loop((regions,years,mp,i,d,z,t)$Bv(regions,years,mp,i,d,z,t),
put  regions.te(regions), years.te(years),mp.te(mp),i.te(i), d.te(d),
z.te(z), t.te(t), Bv(regions,years,mp,i,d,z,t), lat(i), lon(i)/;
);
putclose;

file f_Bv_t /Bv_t.csv/;
f_Bv_t.pc = 5;
put f_Bv_t;
loop((regions,years,mp,i,d,z)$Bv_t(regions,years,mp,i,d,z),
put  regions.te(regions), years.te(years), mp.te(mp),i.te(i), d.te(d),
z.te(d),  Bv_t(regions,years,mp,i,d,z)/;
);
putclose;


file f_Bv_f /Bv_f.csv/;
f_Bv_f.pc = 5;
put f_Bv_f;
loop((regions,years,mp,d,z)$Bv_f(regions,years,mp,d,z),
put  regions.te(regions), years.te(years),mp.te(mp),d.te(d), z.te(z),
Bv_f(regions,years,mp,d,z)/;
);
putclose;

file f_Bv_r /Bv_r.csv/;
f_Bv_r.pc = 5;
put f_Bv_r;
loop((years,mp,d,z)$Bv_r(years,mp,d,z),
put years.te(years),mp.te(mp), d.te(d), z.te(z), Bv_r(years,mp,d,z)/;
);
putclose;
****************************************************************

file f_Biv /Biv.csv/;
f_Biv.pc = 5;
put f_Biv;
loop((regions,years,mp,i,procdo,procset,t)$Biv(regions,years,mp,i,procd
o,procset,t),
put  regions.te(regions), years.te(years),mp.te(mp), i.te(i),
procdo.te(procdo), procset.te(procset),
t.te(t),Biv(regions,years,mp,i,procdo,procset,t)/;
);
putclose;

file f_Biv_t /Biv_t.csv/;
f_Biv_t.pc = 5;
put f_Biv_t;
loop((regions,years,mp,i,procdo,procset)$Biv_t(regions,years,mp,i,procd
o,procset),
put  regions.te(regions), years.te(years), mp.te(mp), i.te(i),
procdo.te(procdo), procset.te(procset),
Biv_t(regions,years,mp,i,procdo,procset)/;
);
putclose;



file f_Biv_f /Biv_f.csv/;
```

```
f_Biv_f.pc = 5;
put f_Biv_f;
loop((regions,years,mp,procdo,procset)$Biv_f(regions,years,mp,procdo,pr
ocset),
put  regions.te(regions), years.te(years),mp.te(mp),procdo.te(procdo),
procset.te(procset), Biv_f(regions,years,mp,procdo,procset)/;
);
putclose;

file f_Biv_r /Biv_r.csv/;
f_Biv_r.pc = 5;
put f_Biv_r;
loop((years,mp,procdo,procset)$Biv_r(years,mp,procdo,procset),
put years.te(years), mp.te(mp),procdo.te(procdo), procset.te(procset),
Biv_r(years,mp,procdo,procset)/;
);
putclose;
*************************************************************************
******
file f_Nv /Nv.csv/;
f_Nv.pc = 5;
put f_Nv;
loop((regions,years,mp,ip,i,procset,t)$Nv(regions,years,mp,ip,i,procset
,t),
put  regions.te(regions), years.te(years), mp.te(mp)ip.te(ip), i.te(i),
t.te(t), procset.te(procset), lat(i), lon(i), lat(ip), lon(ip),
Nv(regions,years,mp,ip,i,procset,t)/;
);
putclose;

file f_Nv_t /Nv_t.csv/;
f_Nv_t.pc = 5;
put f_Nv_t;
loop((regions,years,mp,ip,i,procset)$Nv_t(regions,years,mp,ip,i,procset
),
put  regions.te(regions), years.te(years), mp.te(mp),i.te(i),
ip.te(ip),procset.te(procset),  Nv_t(regions,years,mp,ip,i,procset)/;
);
putclose;


file f_Nv_f /Nv_f.csv/;
f_Nv_f.pc = 5;
put f_Nv_f;
loop((regions,years,mp,procset)$Nv_f(regions,years,mp,procset),
put  regions.te(regions),
mp.te(mp),years.te(years),procset.te(procset),
Nv_f(regions,years,mp,procset)/;
);
putclose;

file f_Nv_r /Nv_r.csv/;
f_Nv_r.pc = 5;
put f_Nv_r;
loop((years,mp,procset)$Nv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),Nv_r(years,mp,procset)/;
);
putclose;
*************************************************************************
******
file f_deliv /deliv.csv/;
f_deliv.pc = 5;
put f_deliv;
```

```
loop((regions,years,mp,procset)$deliv(regions,years,mp,procset),
put  regions.te(regions),
years.te(years),mp.te(mp),procset.te(procset),deliv(regions,years,mp,pr
ocset)/;
);
putclose;

file f_deliv_r /deliv_r.csv/;
f_deliv_r.pc = 5;
put f_deliv_r;
loop((years,mp,procset)$deliv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),deliv_r(years,mp,procset)/;
);
putclose;

***********************************************************************
******
file f_Sv /f_Sv.csv/;
f_Sv.pc = 5;
put f_Sv;
loop((regions,years,mp,i,k,t)$Sv(regions,years,mp,i,k,t),
put regions.te(regions),years.te(years),mp.te(mp), i.te(i), k.te(k),
t.te(t),Sv(regions,years,mp,i,k,t)/;
);
putclose;

file f_Sv_t /f_Sv_t.csv/;
f_Sv_t.pc = 5;
put f_Sv_t;
loop((regions,years,mp,i,k)$Sv_t(regions,years,mp,i,k),
put regions.te(regions),years.te(years),mp.te(mp), i.te(i),
k.te(k),Sv_t(regions,years,mp,i,k) /;
);
putclose;

file f_Sv_f /f_Sv_f.csv/;
f_Sv_f.pc = 5;
put f_Sv_f;
loop((regions,years,mp,k)$Sv_f(regions,years,mp,k),
put regions.te(regions),years.te(years),mp.te(mp),
k.te(k),Sv_f(regions,years,mp,k) /;
);
putclose;

***********************************************************************
******
file f_Siv /f_Siv.csv/;
f_Siv.pc = 5;
put f_Siv;
loop((regions,years,mp,i,k,z,t)$Siv(regions,years,mp,i,k,z,t),
put regions.te(regions),years.te(years), mp.te(mp),i.te(i), k.te(k),
z.te(z), t.te(t),Siv(regions,years,mp,i,k,z,t) /;
);
putclose;

file f_Siv_t /f_Siv_t.csv/;
f_Siv_t.pc = 5;
put f_Siv_t;
loop((regions,years,mp,i,k,z)$Siv_t(regions,years,mp,i,k,z),
put regions.te(regions),years.te(years), mp.te(mp),i.te(i), k.te(k),
z.te(z), Siv_t(regions,years,mp,i,k,z)/;
);
putclose;
```

```
file f_Siv_f /f_Siv_f.csv/;
f_Siv_f.pc = 5;
put f_Siv_f;
loop((regions,years,mp,k,z)$Siv_f(regions,years,mp,k,z),
put regions.te(regions),years.te(years), mp.te(mp),k.te(k), z.te(z),
Siv_f(regions,years,mp,k,z) /;
);
putclose;
***********************************************************************
******
file f_Bpl /f_Bpl.csv/;
f_Bpl.pc = 5;
put f_Bpl;
loop((regions,years,mp,i)$B_plant(regions,years,mp,i),
put i.te(i),regions.te(regions),years.te(years),mp.te(mp),
B_plant(regions,years,mp,i) /;
);
putclose;

file f_Bplr /f_Bplr.csv/;
f_Bplr.pc = 5;

put f_Bplr;
loop((years,mp,i)$B_plant_r(years,mp,i),
put i.te(i),years.te(years),mp.te(mp), B_plant_r(years,mp,i) /;
);
putclose;
```

Fixed Processing Code: Stochastic

```
$TITLE Optimal Design for Biomass Processing and Distribution Network
set i /
$include setreal.inc
/;
alias(i,ip);
set t
/1*14/;

alias(t,tp);
set r
/farm, refinery,terminal/;

set d tasks
/
plant
harvest
proc
wait
/;
alias(d,dp);
set k resources
/
planted
harvested
oil_gal
coming
going
ready
char_ton
MMBTU
clean
dirty
switch_small
switch_med
final_oil
/;

set k3(k)
/
oil_gal
char_ton
MMBTU
final_oil
/;
set make_k(k)
/
switch_small
switch_med
/;

set z size
/
switch
small
med
large
extra
/;

set p
/
b
```

```
a
/;


alias(i,ip);
*alias(t,tp);


set real_arcs(ip,i)
/
$include real_arcs.inc
/;



parameter c_transport1(ip,i)
/
$include cost_100max.inc
/;



parameter central_cost(i)
/
$include terminal_final.inc
/;

parameter pipeline_cost(i)
/
$include pipeline_cost.inc
/;

set f(i)
/
$include set_real2.inc
/;

set l(i)
/
PASCAGOULA_30
/;
set regions
/
$include terminal_set.inc
/;

parameter region_name(i)
/
$include region_name.inc
/;

scalar region_live;



region_live = 1;


set term_seti
/
$include term_set.inc
/;
set years /1978*2052/;
```

```
alias(years,yp);

set sc(yp)
/
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
/;

parameter all_yields(i,sc)
/
$include all_yields.inc
/;


parameter yield_data(i);


set g(f);

set all_sets(f,regions)
/
$include all_sets.inc
/;

g(f) = all_sets(f,'211_79');
yield_data(f) = all_yields(f,'1979');

alias(g,gp);


parameter yielda(f)
/
$include yielda1983.inc
/;

parameter region_rank(regions)
/
206_86 1
218_89 2
203_90 3
232_92 4
243_93 5
248_105 6
211_79 7
/;
parameter yieldb(f)
/
$include avgyieldreal.inc
/;

parameter yieldc(f)
/
$include yielda2005.inc
/;
parameter Land(i)
/
```

```
$include landreal.inc
/;




set procset(z)
/
small
med
large
extra
/;

set procdo(d)
/
proc
/;
parameter lat(i)
/
$include lat.inc
/;
parameter lon(i)
/
$include lon.inc
/;



set term(i)
/
$include terminal_set.inc
/;


set term_set(i,ip)
/
$include terminal_set1.inc
/;


Variables
npv;

positive variables
S(i,k,t,sc)
S1(i,k)
S2(k,t)
pp(i)
De(k,t)
B(i,d,z,t,sc)
Tran(ip,i,k,t,sc)

po
B_tran(k,t)
Deli2(i,k)
S2(k,t)
extra(i,procdo,procset,t)
B1(i,d,z,t);

integer variables
Si(i,k,z,t)
move(i,dp,d,z,t)
```

```
moves(procset)
Bi(i,d,z,t)
Deli(procset)

E(f)


Si1(i,k,d,z,t)
Sid(i,k,d,z,t)
N_tran(ip,i,z,t);

Binary variables
za(i,procset);

Equations

proc1(i,procset,t,sc)

proc2(i)

har3(i,t,sc)
har1(i,t,sc)

oil1(i,t,sc)
oil2(i,t,sc)
planted1(i,t,sc)
planted2(i,t,sc)
planted3(i,t,sc)
planted4(i,t,sc)
processed3(i,t,sc)
costy
plea(i)

;
****************************
set mp /1*5/;
scalar maxp;

parameter caps(mp)
/
1 0.01
2 0.02
3 0.05
4 0.1
5 0.2
/;

maxp = caps('1');
deli.up('small') = 5000;
deli.up('med') = 5000;
alias(i,ip);

parameter beta(t);

beta('1') = 0.95;
beta('2') = 1.0;
beta('3') = 0.95;


set costout /1*20/;
plea(g) .. pp(g) =l= 0.1;
planted1(g,t,sc)$((ord(t) eq 1)  ) .. B(g,'harvest','switch',t,sc) =l=
pp(g);
planted2(g,t,sc)$(ord(t) eq 2   ) ..  B(g,'harvest','switch',t,sc) +
```

```
B(g,'harvest','switch',t-1,sc) =l= pp(g);
planted3(g,t,sc)$(ord(t) eq 3  ) ..  B(g,'harvest','switch',t,sc) +
B(g,'harvest','switch',t-1,sc) + B(g,'harvest','switch',t-2,sc) =l=
pp(g);
planted4(g,t,sc)$(ord(t) ge 4 )  ..  B(g,'harvest','switch',t,sc)  =e=
0;

parameter cnvt(k3)
/
oil_gal 135
char_ton .28
MMBTU 17.55
/;

parameter cvtf(k3)
/
oil_gal 1
char_ton 0.002074
MMBTU .13
/;
parameter arc_pay2(f)
/
$include arc_pay2.inc
/;
har3(g,t,sc)$(ord(t) ge 2)   .. S(g,'harvested',t,sc) =e=
(S(g,'harvested',t-1,sc)*.99125) + (B(g,'harvest','switch',t-
1,sc)*beta(t-1)*all_yields(g,sc))*0.446*Land(g) +
sum(gp$(real_arcs(gp,g)),Tran(gp,g,'harvested',t-1,sc)) -
sum(gp$(real_arcs(g,gp)),Tran(g,gp,'harvested',t,sc)) -
sum((procdo,procset),B(g,procdo,procset,t,sc));


har1(g,t,sc)$(ord(t) eq 1 )  .. S(g,'harvested',t,sc)  =e=  0 -
sum((procdo,procset),B(g,procdo,procset,t,sc)) -
sum(gp$(real_arcs(g,gp)),Tran(g,gp,'harvested',t,sc));



oil1(g,t,sc)$((ord(t) eq 1)   ) .. S(g,'final_oil',t,sc) =e=  0 -
sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t,sc)) + sum(gp$(term_set(gp,g) and
(not term(gp)) and (term(g))),Tran(gp,g,'final_oil',t,sc)) -
Tran(g,'PASCAGOULA_30','final_oil',t,sc)$term(g);
oil2(g,t,sc)$((ord(t) ge 2)    ) .. S(g,'final_oil',t,sc) =e=
S(g,'final_oil',t-1,sc) + sum((procdo,procset),B(g,procdo,procset,t-
1,sc)*.8)- sum(gp$(term_set(g,gp) and term(gp) and (not
term(g))),Tran(g,gp,'final_oil',t,sc)) + sum(gp$(term_set(gp,g) and
(not term(gp)) and (term(g))),Tran(gp,g,'final_oil',t,sc)) -
Tran(g,'PASCAGOULA_30','final_oil',t,sc)$term(g) ;



processed3(i,t,sc)$(l(i) ) .. S(i,'final_oil',t,sc) =e=
S(i,'final_oil',t-1,sc)$(ord(t) ge 2) +
sum((g)$(term(g)),Tran(g,i,'final_oil',t,sc));




parameter maxoo(procset);

maxoo('med') = 3000;
maxoo('small') = 3000*.5;
```

```
parameter maxdo(procset)
/
small 1225000
med 2450000
large 3675000
extra 4900000
/;

parameter costz(procset)
/
small 7728000
med 12768000
large 17808000
extra 22848000
/;

parameter tran_max(procset)
/
small 1100
med 2200
/;

parameter arc_cap(i,ip)
/
$include arc_cap.inc
/;



proc1(g,procset,t,sc) .. B(g,'proc',procset,t,sc) =l=
za(g,procset)*maxdo(procset)*(1/12);

proc2(g) .. sum(procset,za(g,procset)) =l= 1;
/
$include terminal_b.inc
/;

parameter procvar(procset)
/
med 164
small 108
/;

parameter procfix(procset)
/
med 21000
small 10500
/;

parameter costset(procset)
/
med 76000
small 50000
/;

parameter costbig(procset)
/
med 131000
small 87000
/;

parameter costtran(procset)
```

```
/
med 3
small 2
/;

set doplant(d)
/
plant
harvest
/;

parameter costdoplant(doplant)
/
plant 434
harvest 275
/;


parameter cost1(k)
/
harvested 434
final_oil 870000
/;

parameter chold(k)
/
harvested 0.03
/;
parameter procy(procset)
/
small 7700
med 15400
/;

parameter fix(procset)
/
small 424
med 528
/;

parameter fix1(procset)
/
small 1271000
med 1583000
/;

parameter tran3(procset)
/
small 2
med 3
/;

parameter cost_ref(i)
/
$include cost_ref.inc
/;

parameter cost_term(ip,i)
/
$include cost_term.inc
/;

parameter cost_ref1(i)
/
```

```
$include cost_ref1.inc
/;

parameter cost_term1(i)
/
$include terminal_cost.inc
/;

parameter miles_pipe1(i);


set kdo(k)
/
coming
going
/;

miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');


set type
/
oil_val
variable_proc
*fix_tran
unit_cost
char_val
oil_tran_term
oil_tran_truck
plant_cost
variable_tran
/;

parameter costvz(procset)
/
small 13.7
med 11.65
large 10.65
extra 9.97
/;

equations
cost11(sc)
cost2(sc)
cost4(sc)
cost5(sc)
cost6(sc)
cost7(sc)
cost8(sc)
cost9(sc);

set type2(type)
/
oil_val
variable_proc
*fix_tran
*unit_cost
char_val
```

```
oil_tran_term
oil_tran_truck
*plant_cost
variable_tran/;

variable cost(type,sc);

cost11(sc) .. cost('oil_val',sc) =e=
sum(l,S(l,'final_oil','14',sc))*241.8;
cost2(sc) .. cost('variable_proc',sc) =e= - sum((g,procset,t),
B(g,'proc',procset,t,sc)*costvz(procset));

cost4(sc) .. cost('unit_cost',sc) =e= -1*sum((g,procset),
za(g,procset)*costz(procset));
cost5(sc) .. cost('char_val',sc) =e= sum((g,procdo,procset,t)$(ord(t)
le 13), B(g,procdo,procset,t,sc)*6);

cost6(sc) .. cost('oil_tran_term',sc) =e= -
1*sum((g,l,t)$(term(g)),Tran(g,l,'final_oil',t,sc)*pipeline_cost(g)*0.0
161);

cost7(sc) .. cost('oil_tran_truck',sc) =e= -
1*sum((g,gp,t)$((term_set(g,gp) and
term(gp))),Tran(g,gp,'final_oil',t,sc)*cost_term1(g)*.1);
cost8(sc) .. cost('plant_cost',sc) =e= -1*sum((g),pp(g)*Land(g))*322;

cost9(sc) .. cost('variable_tran',sc) =e= -
1*sum((real_arcs(gp,g),t),Tran(gp,g,'harvested',t,sc)*.31*c_transport1(
gp,g));

costy .. npv =e= .1*sum((type2,sc), cost(type2,sc)) -
1*sum(g,pp(g)*Land(g))*322   -1*sum((g,procset),
za(g,procset)*costz(procset)) ;

option lp = cplex;
option mip = cplex;


parameter miles_pipe1(i);
miles_pipe1(i)$(term_set(i,'203_90')) = pipeline_cost('203_90');
miles_pipe1(i)$(term_set(i,'206_86')) = pipeline_cost('206_86');
miles_pipe1(i)$(term_set(i,'211_79')) = pipeline_cost('211_79');
miles_pipe1(i)$(term_set(i,'218_89')) = pipeline_cost('218_89');
miles_pipe1(i)$(term_set(i,'232_92')) = pipeline_cost('232_92');
miles_pipe1(i)$(term_set(i,'248_105')) = pipeline_cost('248_105');
miles_pipe1(i)$(term_set(i,'243_93')) = pipeline_cost('243_93');
parameter miles_term1(i)
/
$include terminal_cost.inc
/;

parameter B_plant(regions,years,mp,i);
parameter B_plant_r(years,mp,i);
parameter miles_term(regions,years,mp,i,t);
parameter miles_term_t(regions,years,mp,i);
parameter miles_term_f(regions,years,mp);


parameter miles_pipe(regions,years,mp,i,t);
parameter miles_pipe_t(regions,years,mp,i);
parameter miles_pipe_f(regions,years,mp);


parameter miles_unit(regions,years,mp,ip,i,procset,t);
```

```
parameter miles_unit_t(regions,years,mp,ip,i,procset);
parameter miles_unit_f(regions,years,mp,procset);
parameter miles_unit_r(years,mp,procset);

parameter miles_unit_num(regions,years,mp,ip,i,procset,t);
parameter miles_unit_t_num(regions,years,mp,ip,i,procset);
parameter miles_unit_f_num(regions,years,mp,procset);
parameter miles_unit_r_num(years,mp,procset);


parameter acres(regions,years,mp,i,t);
parameter acres_t_1(regions,years,mp,i);
parameter acres_t(regions,years,mp,i);
parameter acres_f(regions,years,mp);
parameter acres_r(years,mp);
parameter cost_dat(regions, years,mp,type);
parameter cost_dat_1(years,mp,type);
parameter tons(regions,years,mp,i,t);
parameter tons_t(regions,years,mp,i);
parameter tons_f(regions,years,mp);
parameter tons_r(years,mp);

parameter npvv(regions,mp);


parameter Tranv(regions,years,mp,ip,i,k,t);
parameter Tranv_t(regions,years,mp,ip,i,k);
parameter Tranv_f(regions,years,mp,k);
parameter Tranv_r(years,mp,k);

parameter Bv(regions,years,mp,i,d,z,t);
parameter Bv_t(regions,years,mp,i,d,z);
parameter Bv_f(regions,years,mp,d,z);
parameter Bv_r(years,mp,d,z);

parameter Biv(regions,years,mp,i,d,procset,t);
parameter Biv_t(regions,years,mp,i,d,procset);
parameter Biv_f(regions,years,mp,d,procset);
parameter Biv_r(years,mp,d,procset);

parameter Nv(regions,years,mp,ip,i,procset,t);
parameter Nv_t(regions,years,mp,ip,i,procset);
parameter Nv_f(regions,years,mp,procset);
parameter Nv_r(years,mp,procset);

parameter deliv(regions,years,mp,procset)


parameter Sv(regions,years,mp,i,k,t);
parameter Sv_t(regions,years,mp,i,k);
parameter Sv_f(regions,years,mp,k);

parameter Siv(regions,years,mp,i,k,z,t);
parameter Siv_t(regions,years,mp,i,k,z);
parameter Siv_f(regions,years,mp,k,z);

model model1 /all/;
loop((regions,mp)$(ord(mp) eq 4),
g(f) = all_sets(f,regions);
maxp = caps(mp);

S.l(i,k,t,sc) = 0;

B.l(i,d,z,t,sc) = 0;
```

```
npv.l = 0;
npv.lo = 0;
za.l(i,procset) = 0;
Tran.l(ip,i,k,t,sc) = 0;


 solve model1 using mip maximizing npv;
cost_dat(regions,sc,mp,type) = cost.l(type,sc);

B_plant(regions,years,mp,i) = pp.l(i);

npvv(regions,mp) = npv.l;


deliv(regions,years,mp,procset) = sum(i,za.l(i,procset));

acres(regions,years,mp,i,t) = pp.l(i)*Land(i);
acres_t(regions,years,mp,i) = pp.l(i)*Land(i));
acres_t_1(regions,years,mp,i) = pp.l(i)*Land(i);
acres_f(regions,years,mp) = sum(i,pp.l(i)*Land(i));

parameter npvv_r(mp);

cost_dat_1(sc,mp,type) = sum(regions, cost_dat(regions,sc,mp,type));

npvv_r(mp) = sum(regions, npvv(regions,mp));
parameter deliv_r(years,mp,procset);
deliv_r(years,mp,procset) = sum(regions,
deliv(regions,years,mp,procset));
B_plant_r(years,mp,i) = sum(regions, B_plant(regions,years,mp,i));
acres_r(years,mp) = sum(regions, acres_f(regions,years,mp));


$ontext
1       Acres
2       Tons
3       Planting & Harvest Costs
4       Variable Processing Costs
5       Processor Med
6       Porcessor Small
7       Capacity
8       ton-miles oil truck
9       ton-miles oil pipeline
10      Cost Oil Truck
11      Cost Oil Pipeline
12      Unit Transport Costs
13      Processor Cost
14      Setup Costs
15      Num Moves Small
16     Num Moves Med
17      Oil Value
18      char
19      gas value
20      NPV

$offtext




file f_cost_dat/cost_dat.csv/;
f_cost_dat.pc = 5;
put f_cost_dat;
loop((regions,sc,mp,type)$cost_dat(regions,sc,mp,type),
```

```
put regions.te(regions), sc.te(sc), mp.te(mp),type.te(type),
cost_dat(regions,sc,mp,type)/;
);
putclose;


file f_cost_dat1/cost_dat1.csv/;
f_cost_dat1.pc = 5;
put f_cost_dat1;
loop((sc,type,mp)$cost_dat_1(sc,mp,type),
put  sc.te(sc), mp.te(mp),type.te(type), cost_dat_1(sc,mp,type)/;
);
putclose;

file f_npvv /npvv.csv/;
f_npvv.pc = 5;
put f_npvv;
loop((regions,mp)$npvv(regions,mp),
put  regions.te(regions),  mp.te(mp),npvv(regions,mp)/;
);
putclose;

file f_npvv_r /npvv_r.csv/;
f_npvv_r.pc = 5;
put f_npvv_r;
loop((mp)$npvv_r(mp),
put mp.te(mp), npvv_r(mp)/;
);
putclose;
*******************************

file f_deliv /deliv.csv/;
f_deliv.pc = 5;
put f_deliv;
loop((regions,years,mp,procset)$deliv(regions,years,mp,procset),
put  regions.te(regions),
years.te(years),mp.te(mp),procset.te(procset),
deliv(regions,years,mp,procset)/;
);
putclose;

file f_deliv_r /deliv_r.csv/;
f_deliv_r.pc = 5;
put f_deliv_r;
loop((years,mp,procset)$deliv_r(years,mp,procset),
put years.te(years),mp.te(mp),
procset.te(procset),deliv_r(years,mp,procset)/;
);
putclose;

***********************************************************************
******
```

.

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