UTILIZATION OF BIOMASS ENERGY RESOURCES IN OHIO:

A LINEAR PROGRAMMING MODEL

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SUMMARY

Ohio has a substantial area covered by forests, which ensures abundant supplies of woody biomass. Wood manufacturing companies also generate significant amounts of industrial residues. Current biomass electric technology utilizes both forest biomass and industrial residues and is a viable option for generating commercial electricity. Biomass power plants have a promising future, especially with the prospective regulatory changes that will make the electricity market open for competition. These changes in electrical markets parallel what has happened in the U.S. markets for natural gas and long-distance telecommunication services. Similar regulatory changes in Ohio could make the market for electricity more competitive and provide incentives to utilize biomass resources for electricity generation. Therefore, as an alternative source of energy, biomass power plants show promise for generating commercial energy by using forest and industrial wood residues.

The substantial amounts of biomass resources are generated from forests (tops and limbs) and wood industries (saw dust, chips, bark, edging, etc.). While industrial wood residues are utilized for numerous purposes, forest residues are currently not being used for energy generation, primarily due to the excess supply of industrial wood residues from wood manufacturing companies. Because of their high collection cost, forest residues are not as competitive in price as industrial wood residues, and are therefore left on site. With the prospect of biomass power plants as a viable option commercial energy production in Ohio, forest residues can be utilized effectively to meet the new demands for wood biomass. Plantation forestry could also be practiced in Ohio to supply wood biomass for generating commercial electricity.

This study reviews the current and potential use of wood biomass energy resources. The future generation of commercial electricity from wood biomass would increase the utilization of wood and forest residues in Ohio. A Linear Programming (LP) model is developed to identify potential sites for biomass power plants based on availability of forest and industrial wood residues. This LP model can be used to examine various policy issues having to do with the use and disposal of industrial wood and forest residues in Ohio.

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UTILIZATION OF BIOMASS ENERGY RESOURCES IN OHIO: A LINEAR PROGRAMMING (LP) MODEL

I. INTRODUCTION

Many states in the U.S. are currently considering regulatory changes that will have a major impact on electricity markets. The California Public Utilities Commission recently adopted regulatory changes that will allow industrial customers to buy power directly from whatever supplier they choose, be they brokers, non-utility generators, or existing utility companies (PUCC, 1995). This move towards increased competition in electrical markets parallels what has happened in the U.S. markets for natural gas and long-distance telecommunication services. Similar regulatory changes in Ohio could make the market for electricity more competitive and provide incentives to utilize biomass resources for electricity generation.

Ohio has a substantial area covered by forests, which ensures abundant supplies of woody biomass. Wood manufacturing companies also generate substantial amounts of cheap industrial residues, a part of which is currently being used in existing wood-burning boilers to produce heat and electricity (Shakya, 1995). In general, supplies of industrial wood and forest residues in Ohio are greater than the current demand. However, the situation could change substantially, if the regulatory regime is altered providing incentives to biomass power plants.

Biomass power plants have great potential for generating commercial energy (DOE, 1992; Swezey *et al.*, 1994). Because of the bulk nature of biomass residues, it is important to locate these plants close to sources of biomass supply to minimize the transportation cost. This study developed

a Linear Programming (LP) model to identify potential sites for biomass power plants in Ohio based on availability of forest and industrial wood residues.

1.1 Use of Biomass for Energy Generation

The U.S. Department of Energy (DOE), Biomass Power Program is promoting biomass electric technology as a viable commercial electric generation option (DOE, 1992). The biomass power industry has a promising future, especially with recent and proposed regulatory changes that will make the electricity market open for competition (DOE, 1992; Douglas, 1994; Hyman, 1994; NRRI, 1995; US Congress, 1989). The following are some of the more significant potential changes in the utility industry (DOE, 1992):

- Heightened awareness on the part of utilities and regulators regarding sources of alternative generation with an emphasis on integrated resource planning, energy efficiency, and demand-side management (DSM);

- Increased reliance by the utilities on independent power producers, with a trend toward smaller, incremental additions of power generation;

- Rising concern over the environment as exemplified by the Clean Air Act Amendments of 1990 and numerous state-sponsored environment regulations;

- Changes to Public Utility Regulatory Policies Act (PURPA) in combination with proposed Public Utilities Holding Company Act (PUHCA) modifications which could expand the role of alternative generation sources; and

- Recognition by the Federal Energy Regulatory Commission (FERC) of the inadequacy of existing regulations to provide utility incentives for investments and cost-sharing innovations.

Taking advantage of these regulatory changes, independent power producers can play a major role to produce electricity through the use of an alternative energy source such as woody biomass. Municipal utilities can also develop biomass power to produce commercial energy, especially when there is a plentiful supply of urban wood wastes that would otherwise be land filled (DOE, 1992).

The advantages of biomass energy utilization include (DOE, 1992; Frankena, 1992):

- the use of a renewable resource
- the emission of little or no sulfur or radioactivity
- the emission of low levels of nitrous oxide
- no exacerbation of the acid rain problem
- the emission of zero net CO_2 (carbon dioxide), a suspected cause of global warming
- Increased economic use of industrial wood residues

Biomass power plants also carry environmental risks as well, including:

- Air pollution
- High ash content
- Poor visibility due to air pollutants (particulate)
- Water pollution from soil and nutrient runoff in forests harvested for energy
- Water pollution created by runoff from stockpiles of wood chips, ash, and other conversion and combustion by-products

However, these disadvantages can be minimized to a certain level by implementing pollution control measures and better management strategies. For example, installation of a wet scrubber will capture the particulate emissions. The Mead Paper company in Chillicothe has a wet scrubber in their wood burning boiler, and as a result, their current particulate emissions are well below the permitted levels of US Environmental Protection Agency (EPA). Another effective recycling measure is adopted by the Stone Container in Coshocton in which the local ash company collects and processes the ash from the wood burning plant for the farmland application. Their emissions from the wood burning plant are also within the levels permitted by the USEPA.

1.2 Biomass Energy Utilization in Ohio

Use of biomass energy resources has grown significantly over the last decade. In 1979, power generation from wood and other biomass fuels was less than 200 MW in the country (DOE, 1992). Since then, the Public Utility Regulatory Policies Act of 1978 (PURPA) and tax incentives for non-utility generators (NUGs) have encouraged biomass energy-based power generation. Biomass power plants currently provide more than 50 billion kWh of electric energy from 10,000 MW of installed

capacity in the US (Swezey *et. al.*, 1994). The major source of this capacity is primarily wood-based, and outside utility companies.

Wood is the leading biomass energy resource primarily due to its use as a boiler fuel, both in the pulp and paper as well as forest-product industries. In the US, the lumber industry satisfies close to 75 percent of its energy needs through direct wood combustion while the pulp and paper industry has achieved a 55 percent aggregate fuel contribution from wood (Williams and Porter, 1989). Both heat and electricity are generated from wood using cogeneration technology. In Ohio, Mead Corporation, Hoge Lumber, Sauder Woodworking, and Stone Container Corporation are some of the well-established users of cogeneration technology.

Mead has a wood-fired boiler which is a converted recovery unit and, as such, is not as efficient as others currently in use. Its daily consumption of chips and other residues, which have an average moisture content of 40 percent, is approximately 700 tons. Stone Container's cogeneration system yields 16 MW/hour of electricity, which is equivalent to 40 percent of the factory's requirements, as well as 400,000 pounds/hour of steam, which equals 83 percent of its process heat inputs. Cogeneration has allowed for energy bills to be halved. The wood-fueled boiler consumes 1,200 tons of wood residues per day.

Hoge Lumber Company has two wood-fueled boilers, which together burn 6 tons/hour and produce 3.75 MW of electricity as well as all the steam needed for Hoge's dry kilns and space heating. Sawdust comprises three-quarters of the fuel and wood trim, edging, and bark make up the rest. Hoge's electricity production exceeds the plant's needs. The surplus is sold to the neighboring towns of New Knoxville and Saint Mary's at $0.025/kWh. A daily charge of $0.30/kW is also assessed.

Out of the 26 known wood burning boilers in Ohio, these are just a few examples that illustrate the use of wood biomass for energy generation. There is great potential for additional biomass power plant development, as the state has an enormous biomass resource base both from wood manufacturing companies and forests (tops and limbs). Thirty percent of the total land area in the state is covered by forests, with abundant supply of hardwoods (Erin *et. al.* 1994). In 1991 alone, 525.56 million board feet of saw timber were harvested from Ohio forests (NFES, 1993). A considerable amount of forest residues (tops and limbs) are left on site after the harvesting of saw timber.

These biomass resources both from wood manufacturing companies and forests can be utilized to a greater extent to generate commercial electricity, if the market for independently produced power strengthens. Currently, although a portion of industrial wood residues are being burnt in the existing wood boilers, the use of forest residues is almost negligible. This, however, may change in the future with potential commercial biomass power plants.

The wood manufacturing industry is an important industrial sector in Ohio's economy, with more than 300 sawmills and over 1,000 secondary wood manufacturing companies (Heiligmann *et. al.*, 1993; ODNR, 1993). As part of their production processes, these wood manufacturing industries also generate considerable amounts of wood residues such as sawdust, chips, bark, solid wood trim and edging. Twenty-six known wood manufacturing companies have wood burning boilers which generate both heat and electricity primarily to meet the companies own energy demands (Shakya, 1995). At present, the current supply of industrial wood residues is greater than the demand from these existing wood burning boilers.

1.3 Economic Consequences of Biomass Energy Utilization

If the market for independently produced electricity strengthens, the demand for biomass from forests as well as industrial wood residues, could increase tremendously. At present, there is an excess supply of industrial residues, of which only a portion is used for generating biomass energy. Residues are also used for animal bedding, landscaping, compost, and reconstituted furniture production. A survey of wood manufacturing companies indicates that, on an average, about 15.1 percent of residues are used internally (mainly for wood burning boilers), 37.5 percent are sold, 20.1 percent are just given away, and 27.3 percent are land filled (Shakya, 1995).

Forest residues are mostly left on site, as their high collection costs makes them more expensive to use than industrial wood residues. However, with the prospect of commercial biomass electricity plants, recovery of this resource is being given more serious attention. From an economic standpoint, increased recovery would benefit wood manufacturing companies, which could sell the wood residues to the biomass power plants, especially those that are, at present, freely given away or land filled at a higher cost. Furthermore, there could be an increased recovery of forest residues. Economic benefits would also include creation of new jobs in the wood biomass markets, particularly in collection and supply sectors, as well as in the biomass power plants itself.

1.4 Outline of Report

The next section of this report contains a general overview of the Linear Programming (LP) methodology. This is followed by a description of the LP model developed for this study. The objective of the LP model and its various activities, including specifications of the supply and demand of wood and forests residues, are described in the third section.

The General Algebraic Modeling System (GAMS) software used to write a computer program for this LP model is described in the fourth section on Solving the LP Model. Found there are instructions on how to operate the model which can be modified and edited depending on the purpose of analysis and availability of new information.

The final section of this report discusses the results of LP sample runs taking both the existing situation (base run) and the new demand scenario. The base run result shows the existing demand and supply scenario for wood and forest residues while new demand scenario identifies the supply regions for a new wood burning boiler. The potential sites for biomass power plant establishment are also identified based on the availability of biomass resources. For the purpose of this study, the state of Ohio is regionalized into 50 regions. Their listing and map are presented in the Appendix A. The Appendices also includes the computer program codes of the LP model and its output results.

II. LINEAR PROGRAMMING METHODOLOGY

Linear programming (LP) is the application of the economic concept of constrained optimization to real-world problems and issues. For example, an LP can be set up to identify a mix of inputs and outputs that maximizes a firm's profits subject to regulatory restrictions or limited availability of some given set of resources. Alternatively, a warehouse operator can identify a least-cost delivery scheme with the aid of LP.

All LPS have the same fundamental elements: a objective function; activities/variables; and constraints. First, an objective function has to be specified, it could be either profit maximazation or cost minimization problem. For example, outputs and inputs can be multiplied by their respective prices and the sum, net revenue or profits, becomes the "maximand." Second, a set of activities (in this study, transporting wood and forest residues from supply to demand regions) must be identified. These activities are the LP's variables. Third, constraints (maximum input availability, minimum delivery requirements, etc.) have to be specified.

Any LP "run" indicates the mix of activities that optimizes the objective subject to specified constraints. In addition, "shadow prices" are reported for each constraint. Any such price indicates the value of a unitary relaxation of the corresponding constraint (e.g., the value of making one more unit of a limited resource available). Shadow prices can be used to guide investments aimed at altering constraints.

In addition to making a base case run, which indicates efficient performance of the modeled system under current prices and constraints, alternative runs, reflecting alternative prices and constraints, are possible. This sort of exercise is called "sensitivity analysis" and is particularly useful for quantitative analysis of policy issues and decision-making alternatives.

III. LP MODEL OF THE UTILIZATION OF BIOMASS ENERGY RESOURCES

The Linear Programming (LP) model developed specifically for this study identifies how demand for woody biomass at a given set of cogeneration facilities and power plants can be satisfied at least cost. Currently, there are 26 such facilities located throughout Ohio. A base run, which is discussed later in this report, indicates the most economical way to satisfy their respective demands for feedstock.

In some of the 50 regions into which we have divided the state (Appendix A), virtually all the residual materials generated by manufacturers of wood products is consumed by cogenerators, which also have to obtain some of their supplies from neighboring regions. Elsewhere, at least a portion of those residual materials must be disposed in a landfill or elsewhere, at a cost. In the latter regions, the shadow price of biomass resources is low (indeed, negative), which indicates a potential opportunity to build a profitable new power facility.

Before turning to these and other findings, we will describe the basic elements of the LP model: its objective function and activities, constraints corresponding to biomass demand at energy plants as well as biomass supply at wood manufacturing companies and in forested areas.

3.1 Objective Function and Activities

The objective function (C), which is to be minimized, equals the sum of cost of transporting industrial wood and forest residues among various regions around Ohio (see below) as well as the aggregate land filling cost of industrial wood residues (that are not converted into energy). The objective function, supply and demand activities of the model are given below (the explanation of these equations are given in Appendix B):

$$\text{TOTAL COST} = \Sigma_i \Sigma_j CT * D_{ij} ((CW * X_{ij}) + (CF * Z_{ij})) + \Sigma_i CL * L_i \quad (C)$$

SUBJECT TO,

SUPPLY:

(a) Wood residues availability $\Sigma_j X_{ij} + L_i = X_i$

(b) Forest residues availability $\Sigma_j Z_{ij} <= Z_i$

DEMAND: $\Sigma_i X_{ij} + \Sigma_i Z_{ij} = Y_j$

where:

CF	=	Cost of collecting a ton of forest residues
CL	=	Cost of land filling a ton of wood residues
CT	=	Cost of transporting a ton of residues one mile
CW	=	Cost of wood residues per ton
D_{ij}	=	Miles between center point of region i and j
L_i	=	Tons of wood residues land filled in region i
X_i	=	Tons of wood residues available in region i
Y_j	=	Tons of residues demanded in region j
Z_i	=	Tons of forest residues available in region i
X_{ij}	=	Tons of wood residues shipped from region i to j
Z_{ij}	=	Tons of forest residues shipped from region i to j

The transportation cost of forest and wood residues is based on the rate of $1.75 per 25-ton load per mile, which is equivalent to $0.07 per ton per mile (interview with Mead and Stone Container). It is assumed in the model that the excess supply of wood residues are land filled. The land filling cost is currently at $20 per ton, which includes transportation cost and a land filling fee.

3.2 Regionalization of the State

Ohio is distinguished by its geographical diversity. The Midwestern cornbelt extends into the northern and western parts of the state. By contrast, northeastern Ohio is similar in many respects to Pennsylvania and even New York, while the southeastern part of the state is distinctly Appalachian.

For the purposes of this model, it makes sense to distinguish between the two geologic regions: the unglaciated hill lands in the south, southeast, and east; and the remaining 66 percent of the state's land area that was glaciated. Outside of river valleys and a few other places where fertile soils have built up over time, the former unglaciated lands are not especially suited to agriculture. As a result, forests predominate. For example, Lawrence and Vinton counties, directly south of Columbus, are more than 75 percent forested. In glaciated parts of the state, by contrast, it is rare for forest cover to exceed 25 percent, with the majority being less than 10 percent forested.

Since Ohio's timber resources are concentrated in the unglaciated hill area in the south, southeast, and east, each county located entirely or partially in that area is treated as a separate region for the purposes of the LP model. In the rest of the state, each region comprises two, three, or (in a few cases) four counties. While still respecting county boundaries, we have avoided creating regions in which there are great differences between length and width. Also, an attempt has been made to put large metropolitan areas, where 75 percent of the state's secondary wood manufacturers are located, near the centers of multi-county zones. Thus, for the purposes of our present model, the state is divided into 50 regions. A list and the map of the regions are presented in the Appendix A.

3.3 Modeling of Supply

Using data from a survey of wood manufacturers for wood residues, carried out by this report's coauthor (Shakya, 1995), residue availability in each of the fifty regions was estimated. The Survey reports the availability of industrial wood residues generated in 1993. A Chi-squared test at 5 percent level of significance suggests that the survey data statistically represent the entire wood manufacturing industry. However, availability of wood residues should be interpreted cautiously, especially in the regions where there are large numbers of small- secondary companies, as in Regions 4, 25, and 31. In these regions, although the residues are available in high volume, their collection may not be easy or economical because of the scattered location of small companies. Such problems are considerably minimal in the regions where there are many saw mills and large-secondary companies.

This LP model assumes that all excess supplies of wood residues are land filled. Although wood residues are utilized for various other purposes, these uses are not incorporated in this LP model as the focus of the study is biomass energy generation. Thus, the supply constraint for wood residues on the above equation means the availability of wood residues from the supply region is equal to the supply of wood residues to all the demand regions plus the quantity of wood residues land filled. Based on the field interviews and the survey report on wood residues, the cost of wood residues is estimated to be $8.00 per ton (Shakya, 1995).

Estimates of forest residues are based on data obtained from *Forest Statistics for Ohio, 1991* (NFES, 1993). As a general rule, two tons of forest residues (tops and limbs) are generated from 1000 broad feet saw timber harvesting (Michael Long, ODNR, personal communication, 1995). In 1991, 525.56 million broad feet of saw timber were harvested in Ohio (NFES, 1991). According to this, 1.05 million tons of forest residues were generated in different regions of Ohio. If not collected, forest

residues are left on site. The collection cost for forest residues is estimated to be $15.00 per ton. The supply constraint for forest residues on the above equation describes the supply of forest residues from region "i" to the demand regions is less than or equal to the availability of forest residues in region "i."

3.4 Specification of Demand

There are 26 boiler facilities around the state which are located in 19 regions. Most of these boiler facilities are located in the north-west and the north-east regions of Ohio, while the south-east and the south-west regions have only a few biomass power plants. These 19 regions have demands for wood and forest residues based on their respective boiler capacity.

The average annual woody biomass demand from a biomass power plant is 250,000 tons. In order to minimize costs, energy facilities will first utilize the residues available in their respective regions. The shipment of residues from the supply regions will occur only if the demand of a given boiler is greater than the wood residues available in that region. The demand constraint on the above equation means that the demand for residues in region "j" must be equal to the sum of the supply of wood residues from region "i" to "j," plus the sum of the supply of forest residues from region "i" to "j."

The existing situation in Ohio shows that the current supply of wood and forest residues are higher than the demand from the wood burning boilers. The detailed data for the demand and supply of wood and forest residues by each region are given in the computer program of the transportation LP model. Other necessary variables and parameters are also defined, specified, and explained in the LP model program (see Appendix B).

IV. SOLVING THE LINEAR PROGRAMMING MODEL

This section provides basic instruction on operating and solving the Linear Programming (LP) model. The LP model uses the GAMS (General Algebraic Modeling System) language, which was developed at the World Bank as a general mathematical modeling language. GAMS is widely used as an effective high-level language that provides a compact and concise representation of large and complex models (Brook *et. al.*, 1988; Jefferson and Boisvert, 1989). However, the GAMS model representation can be easily read and modified. This guide explains the basic programming structure for the LP model in GAMS language for the least-cost transportation problem of wood residues in Ohio.

4.1 Installation of GAMS Software

GAMS software should be installed on the hard drive of the computer to run the program. It cannot be used from a computer without a hard drive. There are three software diskettes for GAMS. GAMS is easier to run the program outside Windows or OS/2. The following are the installation steps under DOS command:

I. GAMS is a DOS-based program written in ASCII format. Copy the files from the three diskettes onto a subdirectory called GAMS on the Computer's hard drive.

II. The Computer requires DOS version 5.0 or higher, at least 4 MB of RAMS and 20 MB of hard drive to operate.

III. To install the GAMS software to your computer's hard drive, follow the steps below:

1. Create a directory for GAMS in the hard drive.

   C:\>*md GAMS*

2. Change to GAMS subdirectory.

C:\>*cd GAMS* => C:\GAMS>

3. Copy all the files from the three diskettes into the GAMS subdirectory.

C:\GAMS>*xcopy a:* (for each diskette)

(type *b:* if your floppy drive is b)

4. Execute the "gamsinst" installation program.

C:\GAMS>*gamsinst*

All the files from diskettes are copied and expanded on the hard drive (C:) of the computer. The GAMS software can now be run to solve the program models from the C:\GAMS> subdirectory. However, if the GAMS subdirectory is added in the path by editing *autoexec.bat* file, the GAMS program can be run from any drive or directory.

4.2 Editing and Saving the Model

GAMS software writes the programs as *"ascii"* file which can be easily edited and modified by the DOS editor. The program files have the extensions **.gms*. The name of our model is *LPMOD.GMS*. You can also use any word processing software like Word Perfect or Microsoft Word to modify this model (program file). However, the program files should be saved as a DOS text when using any word processing software. To edit this LP program file by DOS editor, type:

C:\GAMS>*edit lpmod.gms*

The LP model will come up on the screen and you can modify the program. After making the changes, you may want to give a new name to the modified file so that the base model remains unchanged for future reference. GAMS program files should always have **.gms* extension, and this

extension should also be used to name your new program (model) file. You can make several changes at one time or at different times to solve the model simultaneously, in order to analyze the impact of changes in the model. This model can be modified to represent different scenarios on the wood residues market. For example, a change in the demand or the price can be solved for the least-cost transportation schedule in each case.

4.3 Solving the Model and Printing the Output

You can run GAMS to solve the model from any drive, if the GAMS subdirectory is in the path. You can edit the *autoexec.bat* file in the computer's hard drive to add GAMS in the path. It is advisable to create a different subdirectory to save your GAMS program files (models), for example, GAMS-PROG. In this way, all the GAMS program files and the output of the program files will be in one directory, so that it will be easier to locate, modify and solve them. You should be in the same drive or directory where your model/program is saved to run the GAMS solver. For example, when solving the model from C: drive (if your model is saved under GAMS-PROG directory), type:

C:\GAM-PROG>*GAMS LPMOD*

When solving the model from A: drive (if your model is saved in floppy disk in A: drive), type:

A:\>*GAMS LPMOD*

This command will solve the model and a series of iterations will appear on the screen during the solving process. The output of the model will be saved in the **.LST* file (*LPMOD.LST* in this case). The output file contains all the details of the model with the objective function equation, the demand and supply constraints and equations for all regions in the model. The output file also includes the program for the model that is being solved which makes it easier to verify the program.

The output files can be very long depending on the size of the model and its variables. This transportation LP model is an example of a large program in which there are fifty regions with the possibility of transporting wood residues from one given region to another. There are 2500 parameters for the distance among the regions. This makes the objective function as well as the demand and supply equations several pages long. Similarly, the transportation schedule will be fairly lengthy, since it will list all the possible transportation schedules of wood residues from Region 1 to Region 50. However, you can edit the output file and print only the necessary and useful information.

The output file of the LP model is printed and presented as an example in the Appendix. This edited printout result from the LP model output file is only 10 pages, while the whole report of output file is several hundred pages long. It is, therefore, advised that the output file should be edited to print only the necessary information for analysis of the result.

In the output file, the solution report and the summary result are presented. The solution report shows whether a resource was a binding constraint or not. It also provides the upper and lower limits of each of the parameters. The column MARGINAL shows the amounts by which the objective variable would change if the amount of each resource was increase by one unit. The summary result shows the final level of resources use, in this model, the transportation of wood and forest residues from supply to demand regions.

The least-cost transportation LP model written in GAMS language is given in the Appendix. The variables, parameters, and equations in the model are described by deciphering the GAMS codes. GAMS codes are similar to standard mathematical notations and is easy to understand (Brook *et. al.*, 1988). The LP model is solved by using GAMS command as explained earlier and the computer output of the result is given on file (computer disk) called *LPMOD.LST*. This output file is edited for

lengthy equations and other undesirable information for printing. The print out of this output file, result of the transportation LP model, is also presented in the Appendix.

4.4 Application of the LP Model

This LP model can be used to identify the best transportation schedule for any type of use of the residues to a given location, for example, building a reconstituted furniture manufacturer in a certain region. The potential location for establishing a new company can also be identified, based on the availability of residues within a specific mile radius. Any firm or company which uses wood residues as an input could take advantage this LP model to identify ideal locations closer to the residues source points.

The LP model is user friendly and can be modified by adding new information or by altering the existing data in the program. The cost parameters and the demand and supply quantities of wood and forest residues can easily be modified in the model for future uses. For example, if a new wood burning boiler plant is established in Region 27 creating a new demand point of 1000,000 tons of wood residues per year, this new demand can be incorporated in the model to get the new output of transportation schedules (see New Demand Scenario section).

Similarly, an establishment of a wood manufacturer in a certain region would add to the supply of wood residues in that region. The change in transportation or land filling costs can be incorporated in the model by modifying their corresponding values. The concise representation and flexibility of the least-cost transportation LP model are designed for its larger application to address the issues regarding the use and disposal of wood and forest residues in Ohio.

V. SAMPLE RUN

The LP model designed for this study was solved using GAMS software to present and analyze the information generated by the program. The LP model is solved twice separately to analyze both the existing situation and the new demand scenario. The first result generated by the base run case only uses the existing data while the second result in new demand scenario includes an addition of a new demand point in the LP model. The outcome of those results are discussed below. The complete computer programs and their results are presented in the Appendix B, C, and D.

5.1 Base Run Result

The base run LP result uses the existing data in the program. Given that the per-unit transport and land filling costs are $0.07/ton and $20/ton respectively, and given the residues demands and mill waste availability (see Appendix B), the model identifies a least-cost pattern for utilizing and disposing of wood and forest residues. In addition, shadow prices obtained by running the model identify the regions in Ohio where biomass resources are relatively scarce. The latter information is particularly useful in making rational economic decisions regarding the possible locations of cogeneration plants.

Since the existing wood residue availability from wood industries around the state exceeds wood burning boilers' demand by a wide margin, inter-regional shipments are limited. Because of the high collection cost of forest residues and the excess supply of wood residues, it is cheaper to use industrial wood residues rather than forest residues. Therefore, forest residues are utilized at a minimum level in this scenario. However, the data on forest residues provides the biomass base in each region for the future use, if needed.

In this model, there are 19 demand regions for residues, most of which are self-sufficient, except 6 regions (Region 1. Defiance and Williams; Region 2. Fulton, Henry, Lucas, and Wood; Region 18. Coshocton; Region 34. Ross; Region 36. Morgan; and Region 41. Adams). Since the objective of this model is to minimize the cost, wood residues would be supplied to these 6 deficit regions, first from within the same region, next from adjacent regions, and only occasionally from farther away. The average distance that residues are transported is around 45 miles and the maximum haul chosen by the model is 55 miles, from Region 2 to Region 3.

The model assumes that all excess supply of wood residues are land filled. There are currently 8 regions where no land filling takes place while the rest of the regions have excess supply of wood residues. In the case of forest residues, these are not used at present and are left on site as indicated by the results of this model, with the exception of Region 1 (Defiance and Williams).

Shadow prices are given for every demand and supply constraint. The shadow price for any demand point indicates the amount by which the total cost would be raised if there were a one-ton increase in the residue consumption. Each supply region's shadow price indicates the cost impact of a one-ton change in residue availability in that region. The results indicate that the shadow prices in most supply regions correspond to the per-unit land filling costs. This is because of the excess residues availability over the demand. The regions having higher quantities of excess wood residues supply are Region 4 (Cuyahoga, Lorain, Medina, and Summit), Region 11 (Stark and Wayne), Region 24 (Clark, Greene, Miami, and Montgomery), and Region 6 (Mahoning, Portage, and Trumbull), respectively. Since the excess supply of wood residues are land filled, these regions incur high land filling costs. Conversely, these regions can be the potential sites for future biomass energy plants to generate commercial energy from wood residues.

5.2 New Demand Scenario

A new demand point is added in the LP model to analyze the supply of residues from various supply regions. Region 27 is selected as a new demand point for wood/forest residues with an annual demand of 1,000,000 tons. One of the reasons for selecting Region 27 is that it is not close to the existing wood burning facilities so that it will compete minimally for the existing use of wood residues. Other reasons include utilizing wood residues from more than one region, centrally located in Ohio, and also closer to a metropolitan city. This is a hypothetical demand case and can easily be changed to include any other region as a demand point.

The result of this scenario shows that the wood residues are supplied to Region 27 from Regions 16, 26, 27, 28, 29. 35, 36, and 45 (see result in the Appendix). Most of the transportation schedules in the base run case are not changed except in Regions 36 and 41, where there are minor changes in their supply regions. There is no increase in the use of forest residues as the availability of wood residues are high enough to meet the new demand. However, there are now 16 regions that do not landfill wood residues, in comparison to 8 regions in the base run scenario. The results of the output for both base run and new scenario are given in the Appendix C and D respectively.

It is important to note that the base run result is based on the existing demands for residues from wood burning boilers in Ohio, while the new demand scenario result assumes an artificial demand point in Region 27. As explained earlier in this report, other uses of wood residues can be added in this LP model to analyze the transportation schedule and the residue availability scenarios under the new demand. Similarly, sensitivity analysis can be carried out to gauge the impact of per-unit transportation costs, land filling expenses, and other variables.

Presently, forest residues are utilized at a minimum level due to the excess supply of wood residues from wood manufacturing companies. If biomass power plants become viable for commercial energy production in Ohio, the utilization of forest residues may take place in the future. In other states like Vermont, Michigan, Wisconsin, Washington, and Oregon, utilities also operate wood-fired power plants which range from 10 to 50 MW capacity (Swezey *et al.*, 1994). Most of these states also have plantation forestry to produce wood biomass for energy production. Ohio can also grow plantation forestry to supply biomass for generating commercial electricity in the future.

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APPENDICES

APPENDIX A

REGIONS OF OHIO

There are 88 counties in the state of Ohio. The state is grouped into following fifty regions (Map 1):

1. Defiance & Williams
2. Fulton, Henry, Lucas, & Wood
3. Erie, Huron, Ottawa Sandusky, & Seneca
4. Cuyahoga, Lorain, Medina, & Summit
5. Astabula, Geauga, & Lake
6. Mahoning, Portage, & Trumbull
7. Allen, Paulding, Putnam, & Van Wert
8. Hancock & Hardin
9. Crawford & Wyandot
10. Ashland & Richland
11. Stark & Wayne
12. Columbiana
13. Darke & Mercer
14. Auglaize, Champaigne Logan, & Shelby
15. Delaware, Marion, Morrow, & Union
16. Knox & Licking
17. Holmes
18. Coshocton
19. Tuscarawas
20. Carroll
21. Harrison
22. Jefferson
23. Preble
24. Clark, Greene, Miami, & Montgomery
25. Fayette, Franklin, Madison, & Pickaway
26. Fairfield
27. Perry
28. Muskingum
29. Guernsey
30. Belmont
31. Hamilton & Butler
32. Warren & Clinton
33. Highland
34. Ross
35. Hocking
36. Morgan
37. Noble
38. Monroe
39. Clermont
40. Brown
41. Adams
42. Pike
43. Jackson
44. Vinton
45. Athens
46. Washington
47. Scioto
48. Lawrence
49. Gallia
50. Meigs

MAP 1. Regionalization of Ohio into Fifty Zones.

APPENDIX B

COMPUTER PROGRAM OF THE LP MODEL

This model is written in GAMS code for the least-cost transportation problem. The objective of the program is to minimize the transportation cost in order to meet the demand of wood and forest residues at boiler sites from the nearest supply regions. The variables of the model are explained in the computer program below. The description of variables, parameters, and equations are preceded by * sign. This Base Run LP model program is saved under *LPMOD.GMS* name.

```
$TITLE  LP MODEL: A TRANSPORTATION PROBLEM (LPMOD,SEQ=1)
$OFFUPPER
$OFFSYMLIST

* Cost minimization transportation model for wood/forest residues.
* Supply and demand of wood/forest residues among regions in Ohio.
* Model assumes that all the excess wood residues are landfilled.
* However, forest residues are left on site if not collected.

SETS
   I REGIONS
   / R1*R50 / ;
   ALIAS (I,J) ;

PARAMETERS

   X(I)   wood residues available in regions in thousand tons
   /  R1   438.61
      R2  1448.78
      R3   855.74
      R4  2810.76
      R5   992.38
      R6  1569.48
      R7   515.88
      R8   278.80
      R9   171.40
      R10  317.72
      R11 2056.66
      R12  432.00
      R13  432.00
      R14  407.43
      R15  729.42
```

```
   R16  639.92
   R17  992.40
   R18   38.50
   R19 1049.40
   R20    0.84
   R21   81.36
   R22  188.34
   R23  179.66
   R24 1885.56
   R25 1652.40
   R26  261.44
   R27   45.50
   R28  219.00
   R29   18.20
   R30   10.36
   R31 1650.44
   R32  341.96
   R33  250.24
   R34   28.56
   R35  207.38
   R36  189.18
   R37  197.44
   R38   27.24
   R39  251.50
   R40   99.56
   R41  144.22
   R42  279.76
   R43  225.16
   R44  331.72
   R45    9.52
   R46  458.04
   R47   47.60
   R48   28.14
   R49   27.30
   R50   98.30  /

Z(I)   forest residues available in regions in thousand tons
/  R1    5.06
   R2   10.28
   R3   17.58
   R4   43.11
   R5   36.65
   R6   82.90
   R7   13.34
```

```
R8    4.42
R9    3.48
R10   8.39
R11  34.69
R12  12.24
R13   8.36
R14  12.27
R15  13.20
R16  29.27
R17  12.85
R18  25.65
R19  37.51
R20  26.14
R21  26.26
R22  21.70
R23   7.00
R24  23.52
R25   8.80
R26   6.79
R27  18.53
R28  29.24
R29  20.20
R30  22.10
R31   8.39
R32  14.00
R33   9.78
R34  24.64
R35  18.53
R36  32.53
R37   9.61
R38   7.72
R39   5.78
R40  13.79
R41  42.65
R42  46.75
R43  22.67
R44  22.49
R45  23.88
R46  32.53
R47  43.71
R48  14.61
R49  13.26
R50  22.25   /
```

```
Y(J)  quantity demanded in regions in thousand tons
/  R1    900.00
   R2   2000.00
   R3    250.00
   R4      0.00
   R5    250.00
   R6      0.00
   R7    250.00
   R8      0.00
   R9      0.00
   R10     0.00
   R11   250.00
   R12   250.00
   R13     0.00
   R14    52.56
   R15     0.00
   R16     0
   R17    36.50
   R18   438.00
   R19   250.00
   R20     0
   R21     0
   R22    62.00
   R23     0
   R24   250.00
   R25   250.00
   R26     0
   R27     0
   R28     0
   R29     0
   R30     0
   R31   250.00
   R32     0
   R33     0
   R34   255.50
   R35     0
   R36   250.00
   R37     0
   R38     0
   R39     0
   R40     0
   R41   250.00
   R42    19.25
   R43     0
```

```
     R44      0
     R45      0
     R46      0
     R47      0
     R48      0
     R49      0
     R50      0    / ;
```

TABLE D(I,J) distance in miles between regions

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	15	45	95	155	205	205	45	65	85	115
R2	45	25	55	115	165	165	45	45	65	95
R3	95	55	25	55	115	115	85	55	35	45
R4	155	115	55	25	55	45	145	105	85	45
R5	205	165	115	55	15	35	195	165	135	115
R6	205	165	115	45	35	25	185	155	125	85
R7	45	45	85	145	195	185	25	45	75	105
R8	65	45	55	105	165	155	45	15	35	75
R9	85	65	35	85	135	125	75	35	15	45
R10	115	95	45	45	115	85	105	75	45	15
R11	165	135	75	35	75	45	145	115	85	45
R12	215	175	115	75	65	35	195	165	135	95
R13	75	95	115	175	225	215	55	65	95	135
R14	85	85	95	145	95	185	55	45	65	95
R15	105	95	65	95	145	135	75	45	35	55
R16	145	115	75	85	125	105	115	75	55	45
R17	155	125	75	55	95	75	135	105	75	35
R18	165	135	85	75	115	85	145	105	85	45
R19	185	145	95	65	85	65	165	125	95	65
R20	205	165	115	65	75	45	185	145	115	75
R21	205	175	115	85	95	65	185	145	125	85
R22	225	195	135	85	95	65	205	165	145	105
R23	115	115	145	195	245	235	85	95	115	155
R24	115	115	125	165	215	195	85	75	95	115
R25	135	115	105	135	185	165	105	85	75	85
R26	165	145	115	125	165	145	135	105	85	75
R27	175	155	115	115	155	125	145	115	95	75
R28	175	145	105	95	135	115	145	115	95	65
R29	195	165	115	95	115	95	175	135	105	75
R30	225	195	135	105	115	85	205	165	135	105
R31	115	165	175	215	265	245	115	125	135	165
R32	145	145	145	185	235	215	115	115	115	135
R33	165	165	155	185	235	205	135	125	125	135
R34	175	165	145	155	225	175	135	115	115	115

R35	185	155	125	135	175	145	145	125	115	95
R36	195	175	135	125	155	125	175	135	115	95
R37	215	175	135	115	135	105	185	145	125	95
R38	225	195	155	115	135	115	205	165	145	105
R39	175	175	175	205	265	235	135	135	145	165
R40	185	185	175	205	255	235	145	145	145	165
R41	195	185	185	205	245	225	155	145	145	155
R42	185	175	155	175	215	195	155	135	125	135
R43	205	185	165	165	205	185	165	145	135	135
R44	195	175	145	155	195	165	165	135	125	115
R45	205	185	155	145	185	155	175	145	135	115
R46	225	195	155	135	165	125	195	155	135	105
R47	205	195	175	195	235	205	165	155	155	145
R48	235	225	195	205	245	205	195	175	165	165
R49	225	215	185	185	215	185	185	165	155	145
R50	215	195	165	155	195	105	185	155	145	125

+	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20
R1	165	215	75	85	105	145	155	165	185	205
R2	135	175	95	85	95	115	125	135	145	165
R3	75	115	115	95	65	75	75	85	95	115
R4	35	75	175	145	95	85	55	75	65	65
R5	75	65	225	195	145	125	95	115	85	75
R6	45	75	215	185	135	105	75	85	65	45
R7	145	195	55	55	75	115	135	145	165	185
R8	115	165	65	45	45	75	105	105	125	145
R9	85	135	95	65	35	55	75	85	95	115
R10	45	95	135	95	55	45	35	45	65	75
R11	15	55	175	135	85	65	25	45	25	35
R12	55	15	225	195	135	105	65	75	45	25
R13	175	225	25	35	85	125	155	155	175	125
R14	135	195	35	25	55	85	125	115	145	165
R15	85	135	85	55	25	45	75	75	95	115
R16	65	105	125	85	45	25	35	35	55	85
R17	25	65	155	125	75	35	5	25	25	45
R18	45	75	155	115	75	35	25	5	25	55
R19	25	45	175	145	95	55	25	25	15	25
R20	35	25	125	165	115	85	45	55	25	5
R21	45	45	125	165	115	75	45	45	25	25
R22	65	35	225	185	135	95	65	65	45	25
R23	185	235	45	55	115	135	165	165	195	215
R24	155	195	55	45	75	95	135	125	155	175
R25	115	155	85	55	55	55	95	85	115	135
R26	95	125	125	95	65	45	75	55	85	105

R27	85	115	145	115	75	45	65	45	65	95
R28	65	85	155	125	75	35	45	25	45	65
R29	55	65	175	145	95	55	45	25	35	55
R30	65	55	205	175	125	85	75	55	45	45
R31	195	245	75	85	115	145	175	165	195	215
R32	165	205	75	75	95	105	145	135	165	185
R33	165	195	105	85	95	105	135	125	155	175
R34	135	165	115	95	85	75	115	95	125	145
R35	105	135	135	105	75	55	85	65	95	105
R36	85	105	165	135	95	65	75	55	65	85
R37	75	85	185	155	105	65	65	45	65	65
R38	85	85	205	175	125	85	75	65	55	65
R39	195	235	95	95	115	135	165	155	185	205
R40	185	225	115	105	115	125	165	155	175	195
R41	175	205	125	115	115	125	155	145	165	185
R42	145	175	125	105	95	95	125	115	135	155
R43	135	165	145	125	105	95	115	105	125	145
R44	125	145	145	125	95	75	95	85	105	125
R45	115	125	165	135	105	75	95	75	95	195
R46	95	105	195	155	115	85	85	65	75	85
R47	165	185	145	125	115	105	135	125	145	165
R48	175	185	175	155	145	125	145	125	155	105
R49	145	165	175	145	125	105	125	105	135	145
R50	125	135	175	145	115	85	105	85	105	125

+	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30
R1	205	225	115	115	135	165	175	175	195	225
R2	175	195	115	115	115	145	155	145	165	195
R3	115	135	145	125	105	115	115	105	115	135
R4	85	85	195	165	135	125	115	95	95	105
R5	95	95	245	215	185	165	155	135	115	115
R6	65	65	235	195	165	145	125	115	95	85
R7	185	205	85	85	105	135	145	145	175	205
R8	145	165	95	75	85	105	115	115	135	165
R9	125	145	115	95	75	85	95	95	105	135
R10	85	105	155	115	85	75	75	65	75	105
R11	45	65	185	155	115	95	85	65	55	65
R12	45	35	235	195	155	125	115	85	65	55
R13	125	225	45	55	85	125	145	155	175	205
R14	165	185	55	45	55	95	115	125	145	175
R15	115	135	115	75	55	65	75	75	95	125
R16	75	95	135	95	55	45	45	35	55	85
R17	45	65	165	135	95	75	65	45	45	75
R18	45	65	165	125	85	55	45	25	25	55

R19	25	45	195	155	115	85	65	45	35	45
R20	25	25	215	175	135	105	95	65	55	45
R21	5	25	205	175	125	95	75	55	35	25
R22	25	5	225	195	155	115	95	75	55	35
R23	205	225	5	35	85	115	145	155	185	215
R24	175	195	35	25	45	85	105	125	135	175
R25	125	155	85	45	35	45	65	75	105	135
R26	95	115	115	85	45	5	25	45	65	95
R27	75	95	145	105	65	25	5	25	45	75
R28	55	75	155	125	75	45	25	5	25	55
R29	35	55	185	145	105	65	45	25	5	35
R30	25	35	215	175	135	95	75	55	35	5
R31	215	235	35	55	85	115	145	155	185	215
R32	175	195	45	35	55	85	105	125	155	175
R33	165	185	75	55	55	75	95	115	135	165
R34	135	155	95	75	45	45	65	85	105	135
R35	95	115	135	95	55	25	25	45	65	95
R36	65	85	165	125	85	45	25	25	35	65
R37	45	65	185	145	105	65	45	35	25	35
R38	45	55	205	175	125	85	65	55	35	25
R39	195	225	55	55	75	105	125	145	175	195
R40	185	215	75	65	75	95	115	135	165	185
R41	175	195	95	85	75	85	95	125	145	175
R42	145	165	105	85	55	55	65	95	115	135
R43	125	145	135	105	75	55	55	85	105	125
R44	105	125	135	105	65	35	45	65	85	115
R45	95	105	155	125	85	45	35	55	65	85
R46	65	75	185	155	105	65	45	45	45	55
R47	155	175	115	95	75	75	85	105	125	145
R48	155	165	145	125	105	85	85	105	115	145
R49	135	145	155	125	95	75	65	85	105	115
R50	105	115	165	135	95	65	45	65	75	95

+	R31	R32	R33	R34	R35	R36	R37	R38	R39	R40
R1	155	145	165	175	185	195	215	225	175	185
R2	165	145	165	165	155	175	175	195	175	185
R3	175	145	155	145	125	135	135	155	175	175
R4	215	185	185	155	135	125	115	115	205	205
R5	265	235	235	225	175	155	135	135	265	255
R6	245	215	205	175	145	125	105	115	235	235
R7	115	115	135	135	145	175	185	205	135	145
R8	125	115	125	115	125	135	145	165	135	145
R9	135	115	125	115	115	115	125	145	145	145
R10	165	135	135	115	95	95	95	105	165	165

R11	195	165	165	135	105	85	75	85	195	185
R12	245	205	195	165	135	105	85	85	235	225
R13	75	75	105	115	135	165	185	205	95	115
R14	85	75	85	95	105	135	155	175	95	105
R15	115	95	95	85	75	95	105	125	115	115
R16	145	105	105	75	55	65	65	85	135	125
R17	175	145	135	115	85	75	65	75	165	165
R18	165	135	125	95	65	55	45	65	155	155
R19	195	165	155	125	95	65	55	55	185	175
R20	215	185	175	145	105	85	65	65	205	195
R21	215	175	165	135	95	65	45	45	195	185
R22	235	195	185	155	115	85	65	55	225	215
R23	35	45	75	95	135	165	185	205	55	75
R24	55	35	55	75	95	125	145	175	55	65
R25	85	55	55	45	55	85	105	125	75	75
R26	115	85	75	45	25	45	65	85	105	95
R27	145	105	95	65	25	25	45	65	125	115
R28	155	125	115	85	45	25	35	55	145	145
R29	185	155	135	105	65	35	25	35	175	165
R30	215	175	165	135	95	65	35	25	195	185
R31	15	35	55	85	125	155	185	205	25	55
R32	35	15	25	55	95	125	145	165	35	35
R33	55	25	15	35	75	105	135	155	35	25
R34	85	55	35	15	35	75	95	115	75	55
R35	125	95	75	35	5	35	65	85	105	95
R36	155	125	105	75	35	5	25	45	145	125
R37	185	145	135	95	65	25	5	25	165	155
R38	205	165	155	115	85	45	25	5	185	175
R39	25	35	35	75	105	145	165	185	5	25
R40	55	35	25	55	95	125	155	175	25	15
R41	75	55	25	45	75	115	135	155	45	25
R42	95	65	35	25	45	85	105	125	65	55
R43	115	85	65	35	45	65	85	105	95	75
R44	125	95	75	35	25	45	65	85	105	85
R45	155	115	95	55	35	25	45	65	125	115
R46	185	145	125	95	55	25	25	35	165	145
R47	95	75	45	35	55	85	115	125	75	55
R48	135	105	85	65	75	85	105	125	105	85
R49	135	105	85	55	55	65	85	105	115	95
R50	145	115	95	65	45	45	55	75	125	115

+	R41	R42	R43	R44	R45	R46	R47	R48	R49	R50
R1	195	185	205	195	205	225	205	235	225	215
R2	185	175	185	175	185	195	195	225	215	195

R3	185	155	165	145	155	155	175	195	185	165
R4	205	175	165	155	145	135	195	205	185	155
R5	245	215	205	195	185	165	235	245	215	195
R6	225	195	185	165	155	125	205	205	185	165
R7	155	155	165	165	175	195	165	195	185	185
R8	145	135	145	135	145	155	155	175	165	155
R9	145	125	135	125	135	135	155	165	155	145
R10	155	135	135	115	115	105	145	165	145	125
R11	175	145	135	125	115	95	165	175	145	125
R12	205	175	165	145	125	105	185	185	165	135
R13	125	125	145	145	165	195	145	175	175	175
R14	115	105	125	125	135	155	125	155	145	145
R15	115	95	105	95	105	115	115	145	125	115
R16	125	95	95	75	75	85	105	125	105	85
R17	155	125	115	95	95	85	135	145	125	105
R18	145	115	105	85	75	65	125	125	105	85
R19	165	135	125	105	95	75	145	155	135	105
R20	185	155	145	125	195	85	165	165	145	125
R21	175	145	125	105	95	65	155	155	135	105
R22	195	165	145	125	105	75	175	165	145	115
R23	95	105	135	135	155	185	115	145	155	165
R24	85	85	105	105	125	155	95	125	125	135
R25	75	55	75	65	85	105	75	105	95	95
R26	85	55	55	35	45	65	75	85	75	65
R27	95	65	55	45	35	45	85	85	65	45
R28	125	95	85	65	55	45	105	105	85	65
R29	145	115	105	85	65	45	125	115	105	75
R30	175	135	125	115	85	55	145	145	115	95
R31	75	95	115	125	155	185	95	135	135	145
R32	55	65	85	95	115	145	75	105	105	115
R33	25	35	65	75	95	125	45	85	85	95
R34	45	25	35	35	55	95	35	65	55	65
R35	75	45	45	25	35	55	55	75	55	45
R36	115	85	65	45	25	25	85	85	65	45
R37	135	105	85	65	45	25	115	105	85	55
R38	155	125	105	85	65	35	125	125	105	75
R39	45	65	95	105	125	165	75	105	115	125
R40	25	55	75	85	115	145	55	85	95	115
R41	15	35	55	75	95	135	35	65	75	95
R42	35	15	25	45	65	95	45	25	45	65
R43	55	25	5	25	35	75	25	35	25	35
R44	75	45	25	5	25	65	45	55	35	35
R45	95	65	35	25	5	35	65	65	45	25
R46	135	95	75	65	35	15	95	95	75	45

```
R47 35   25   25   45   65   95   15   35   45   65
R48 65   45   35   55   65   95   35   5    25   55
R49 75   45   25   35   45   75   45   25   5    35
R50 95   65   35   35   25   45   65   55   35   5  ;
```

```
SCALAR CT  transportation cost per ton per mile          /  0.07 / ;
SCALAR CW cost of wood residues per ton                  /  8.00 / ;
SCALAR CF  collection cost of forest residues per ton    / 15.00 / ;
SCALAR CL  landfilling cost per ton                      / 20.00 / ;
```

* Forest residues are collected from forests before transportation and CF is the cost of collection. These residues are left on site if not collected.

```
PARAMETER C(I,J)  transportation cost in dollars among regions;
      C(I,J) = CT*D(I,J);

VARIABLES
        XT(I,J)        shipment of wood residues among regions
        ZT(I,J)        shipment of forest residues among regions
        XL(I)          quantity of wood residues landfilled in region I
        TOTCOST        total cost;

              POSITIVE VARIABLE  XT ;
              POSITIVE VARIABLE  ZT ;
              POSITIVE VARIABLE  XL ;

EQUATIONS

 MINCOST     objective function
 WOOD(I)     quantities of wood residues supplied from region I
 FOREST(I)   quantities of forest residues supplied from region I
 DEMAND(J) quantities demanded in region J  ;

 MINCOST ..  SUM ( (I,J), C(I,J)  *  ( ( CW*XT(I,J) ) +
                 (CF*ZT(I,J)))) + (CL*SUM(I, XL(I)))  =E=  TOTCOST;
```

* This is objective function of the model which minimizes sum of transportation cost of wood and forest residues, and sum of landfilling cost of wood residues for all fifty regions. There is a collection cost (CF) for the use of forest residues.

```
 WOOD(I) ..  SUM(J, XT(I,J)) + XL(I)  =E=  X(I)  ;
```

```
* Supply constraint for wood residues: total supply of wood residues to all the demand regions from
      region I plus wood residues landfilled in region I is equal to the wood residues available in
      region I.

FOREST(I) .. SUM(J, ZT(I,J))        =L=  Z(I) ;

* Supply constraint for forest residues: total supply of forest residues from region I to all the demand
      regions is less than the forest residues available in region I.

DEMAND(J) .. SUM(I,XT(I,J)) + SUM(I,ZT(I,J))  =E= Y(J)$Y(J);

* Demand of residues in region J is equal to the supply of wood and forest residues from all regions
      to region J.


MODEL LPMOD  /ALL/ ;    * model will use all the equations.

OPTION LIMROW = 1;              * output will display one equation each
                                      for supply and demand constraints.
OPTION LIMCOL = 2;

SOLVE LPMOD MINIMIZING TOTCOST USING LP;

* Command to solve the LPMOD model to minimize total cost.


DISPLAY XT.L, ZT.L ;        * Output file will display the quantities of wood and forest residues
                                  supplied from regions I to  J.
```

APPENDIX C

LP MODEL: A TRANSPORTATION PROBLEM RESULTS (OUTPUT OF BASE RUN SCENARIO)

Symbol Listing

SETS

I	REGIONS
J	Aliased with I

PARAMETERS

C	transportation cost in dollars among regions
CF	collection cost of forest residues per ton
CL	landfilling cost per ton
CT	trasportation cost per ton per mile
CW	cost of wood residues per ton
D	distance in miles between regions
X	wood residues available in regions in thousand tons
Y	quantity demanded in regions in thousand tons
Z	forest residues available in regions in thousand tons

VARIABLES

TOTCOST	total cost
XL	quantity of wood residues landfilled in region I
XT	shipment of wood residues among regions
ZT	shipment of forest residues among regions

EQUATIONS

DEMAND	quantities demanded in region J
FOREST	quantities of forest residues supplied from region I
MINCOST	objective function
WOOD	quantities of wood residues supplied from region I

MODELS LPMOD

```
COMPILATION TIME     =        0.280 SECONDS        VERID MW2-00-064
Equation Listing    SOLVE LPMOD USING LP FROM LINE 469
```

```
---- MINCOST     =E=  objective function

MINCOST..  8.4*XT(R1,R1) +  25.2*XT(R1,R2) +  53.2*XT(R1,R3)   +
          86.8*XT(R1,R4) + 114.8*XT(R1,R5) + 114.8*XT(R1,R6)...  +
          30.8*XT(R50,R48) + 19.6*XT(R50,R49) + 2.8*XT(R50,R50)  +
          15.75*ZT(R1,R1) + 47.25*ZT(R1,R2) + 99.75*ZT(R1,R3)... +
          57.75*ZT(R50,R48) + 36.75*ZT(R50,R49) + 5.25*ZT(R50,R50)+
          20*XL(R1) + 20*XL(R2) + 20*XL(R3)... + 20*XL(R48) +
          20*XL(R49)+ 20*XL(R50) - TOTCOST =E= 0 ; (LHS = 0)

---- WOOD  =E=  quantities of wood residues supplied from region I

WOOD(R1)..  XT(R1,R1) + XT(R1,R2) + XT(R1,R3) + XT(R1,R4)... +
            XT(R1,R49) + XT(R1,R50) + XL(R1) =E= 438.61 ; (LHS = 0)
REMAINING 49 ENTRIES SKIPPED


-- FOREST =L= quantities of forest residues supplied from region I

FOREST(R1)..   ZT(R1,R1) + ZT(R1,R2) + ZT(R1,R3) + ZT(R1,R4)... +
               ZT(R1,R49) + ZT(R1,R50) =L= 5.06 ; (LHS = 0)
REMAINING 49 ENTRIES SKIPPED


---- DEMAND  =E=  quantities demanded in region J

DEMAND(R1)..   XT(R1,R1) + XT(R2,R1) + XT(R3,R1) + XT(R4,R1)... +
               XT(R49,R1) + XT(R50,R1) + ZT(R1,R1) + ZT(R2,R1) +
               ZT(R3,R1)... + ZT(R49,R1) + ZT(R50,R1) =E= 900 ;
               (LHS = 0 ***)
REMAINING 49 ENTRIES SKIPPED


Column Listing      SOLVE LPMOD USING LP FROM LINE 469

---- XT         shipment of wood residues among regions

XT(R1,R1)
                (.LO, .L, .UP = 0, 0, +INF)
        8.4     MINCOST
        1 WOOD(R1)
        1 DEMAND(R1)
```

S O L V E S U M M A R Y

MODEL	LPMOD	OBJECTIVE	TOTCOST
TYPE	LP	DIRECTION	MINIMIZE
SOLVER	MINOS5	FROM LINE	469

```
**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL
**** OBJECTIVE VALUE          476516.0670

 RESOURCE USAGE, LIMIT          1.600      1000.000
 ITERATION COUNT, LIMIT       137          2000
 Work space allocated           --     0.77 Mb
```

-- EQU WOOD quantities of wood residues supplied from region I

	LOWER	LEVEL	UPPER	MARGINAL
R1	438.610	438.610	438.610	-13.600
R2	1448.780	1448.780	1448.780	3.200
R3	855.740	855.740	855.740	20.000
R4	2810.760	2810.760	2810.760	20.000
R5	992.380	992.380	992.380	20.000
R6	1569.480	1569.480	1569.480	20.000
R7	515.880	515.880	515.880	3.200
R8	278.800	278.800	278.800	14.400
R9	171.400	171.400	171.400	20.000
R10	317.720	317.720	317.720	20.000
R11	2056.660	2056.660	2056.660	20.000
R12	432.000	432.000	432.000	20.000
R13	432.000	432.000	432.000	20.000
R14	407.430	407.430	407.430	20.000
R15	729.420	729.420	729.420	20.000
R16	639.920	639.920	639.920	20.000
R17	992.400	992.400	992.400	20.000
R18	38.500	38.500	38.500	8.800
R19	1049.400	1049.400	1049.400	20.000
R20	0.840	0.840	0.840	20.000
R21	81.360	81.360	81.360	20.000
R22	188.340	188.340	188.340	20.000
R23	179.660	179.660	179.660	20.000
R24	1885.560	1885.560	1885.560	20.000
R25	1652.400	1652.400	1652.400	20.000
R26	261.440	261.440	261.440	20.000

```
XT(R1,R2)
                (.LO, .L, .UP = 0, 0, +INF)
       25.2     MINCOST
        1 WOOD(R1)
        1 DEMAND(R2)
REMAINING 2498 ENTRIES SKIPPED

-- ZT   shipment of forest residues among regions

ZT(R1,R1)
                (.LO, .L, .UP = 0, 0, +INF)
       15.75    MINCOST
        1 FOREST(R1)
        1 DEMAND(R1)
ZT(R1,R2)
                (.LO, .L, .UP = 0, 0, +INF)
       47.25    MINCOST
        1 FOREST(R1)
        1 DEMAND(R2)
REMAINING 2498 ENTRIES SKIPPED
-- XL     quantity of wood residues landfilled in region I

XL(R1)
                (.LO, .L, .UP = 0, 0, +INF)
       20       MINCOST
        1       WOOD(R1)
XL(R2)
                (.LO, .L, .UP = 0, 0, +INF)
       20       MINCOST
        1       WOOD(R2)
REMAINING 48 ENTRIES SKIPPED

Model Statistics    SOLVE LPMOD USING LP FROM LINE 469

MODEL STATISTICS

BLOCKS OF EQUATIONS        4     SINGLE EQUATIONS       151
BLOCKS OF VARIABLES        4     SINGLE VARIABLES      5051
NON ZERO ELEMENTS      15101

GENERATION TIME      =        2.910 SECONDS

EXECUTION TIME                3.020 SECONDS        VERID MW2-00-064
```

R27	45.500	45.500	45.500	20.000
R28	219.000	219.000	219.000	20.000
R29	18.200	18.200	18.200	20.000
R30	10.360	10.360	10.360	20.000
R31	1650.440	1650.440	1650.440	20.000
R32	341.960	341.960	341.960	20.000
R33	250.240	250.240	250.240	20.000
R34	28.560	28.560	28.560	14.400
R35	207.380	207.380	207.380	20.000
R36	189.180	189.180	189.180	8.800
R37	197.440	197.440	197.440	20.000
R38	27.240	27.240	27.240	20.000
R39	251.500	251.500	251.500	20.000
R40	99.560	99.560	99.560	20.000
R41	144.220	144.220	144.220	14.400
R42	279.760	279.760	279.760	20.000
R43	225.160	225.160	225.160	20.000
R44	331.720	331.720	331.720	20.000
R45	9.520	9.520	9.520	20.000
R46	458.040	458.040	458.040	20.000
R47	47.600	47.600	47.600	20.000
R48	28.140	28.140	28.140	20.000
R49	27.300	27.300	27.300	20.000
R50	98.300	98.300	98.300	20.000

-- EQU FOREST quantities of forest residues supplied from region I

	LOWER	LEVEL	UPPER	MARGINAL
R1	-INF	5.060	5.060	-6.250
R2	-INF	.	10.280	.
R3	-INF	.	17.580	.
R4	-INF		43.110	
R5	-INF		36.650	
R6	-INF		82.900	
R7	-INF		13.340	
R8	-INF		4.420	
R9	-INF		3.480	
R10	-INF		8.390	.
R11	-INF	.	34.690	.
R12	-INF	.	12.240	.
R13	-INF	.	8.360	.
R14	-INF	.	12.270	.
R15	-INF		13.200	
R16	-INF		29.270	

R17	-INF		12.850
R18	-INF		25.650
R19	-INF		37.510
R20	-INF	.	26.140
R21	-INF	.	26.260
R22	-INF	.	21.700
R23	-INF	.	7.000
R24	-INF		23.520
R25	-INF		8.800
R26	-INF		6.790
R27	-INF		18.530
R28	-INF		29.240
R29	-INF		20.200
R30	-INF		22.100
R31	-INF	.	8.390
R32	-INF	.	14.000
R33	-INF	.	9.780
R34	-INF	.	24.640
R35	-INF	.	18.530
R36	-INF		32.530
R37	-INF		9.610
R38	-INF		7.720
R39	-INF		5.780
R40	-INF		13.790
R41	-INF		42.650
R42	-INF	.	46.750
R43	-INF	.	22.670
R44	-INF	.	22.490
R45	-INF	.	23.880
R46	-INF		32.530
R47	-INF		43.710
R48	-INF		14.610
R49	-INF		13.260
R50	-INF		22.250

-- EQU DEMAND quantities demanded in region J

	LOWER	LEVEL	UPPER	MARGINAL
R1	900.000	900.000	900.000	22.000
R2	2000.000	2000.000	2000.000	10.800
R3	250.000	250.000	250.000	-6.000
R4	.	.	.	-6.000
R5	250.000	250.000	250.000	-11.600
R6	.	.	.	-6.000

R7	250.000	250.000	250.000	10.800
R8	.	.		-6.000
R9	.	.		-11.600
R10	.	.	.	-11.600
R11	250.000	250.000	250.000	-11.600
R12	250.000	250.000	250.000	-11.600
R13	.	.	.	-6.000
R14	52.560	52.560	52.560	-6.000
R15	.	.		-6.000
R16	.	.	.	-6.000
R17	36.500	36.500	36.500	-17.200
R18	438.000	438.000	438.000	-6.000
R19	250.000	250.000	250.000	-11.600
R20	.	.		-17.200
R21	.	.	.	-17.200
R22	62.000	62.000	62.000	-17.200
R23	.	.	.	-17.200
R24	250.000	250.000	250.000	-6.000
R25	250.000	250.000	250.000	-0.400
R26	.	.		-17.200
R27	.	.		-17.200
R28	.	.		-17.200
R29	.	.		-17.200
R30	.	.	.	-17.200
R31	250.000	250.000	250.000	-11.600
R32	.	.		-11.600
R33	.	.	.	-11.600
R34	255.500	255.500	255.500	-6.000
R35	.	.	.	-17.200
R36	250.000	250.000	250.000	-6.000
R37	.	.		-17.200
R38	.	.		-17.200
R39	.	.		-17.200
R40	.	.	.	-11.600
R41	250.000	250.000	250.000	-6.000
R42	19.250	19.250	19.250	-11.600
R43	.	.		-17.200
R44	.	.		-17.200
R45	.	.	.	-17.200
R46	.	.	.	-11.600
R47	.	.		-11.600
R48	.	.		-17.200
R49	.	.		-17.200
R50	.	.		-17.200

-- VAR XL quantity of wood residues landfilled in region I

	LOWER	LEVEL	UPPER	MARGINAL
R1	.	.	+INF	33.600
R2		.	+INF	16.800
R3		333.320	+INF	.
R4		2810.760	+INF	.
R5		742.380	+INF	.
R6		1569.480	+INF	.
R7		.	+INF	16.800
R8		.	+INF	5.600
R9		171.400	+INF	.
R10		317.720	+INF	
R11		1806.660	+INF	
R12		182.000	+INF	
R13		432.000	+INF	
R14		164.420	+INF	
R15	.	729.420	+INF	
R16	.	639.920	+INF	
R17	.	556.400	+INF	.
R18	.	.	+INF	11.200
R19	.	799.400	+INF	
R20		0.840	+INF	
R21		81.360	+INF	
R22		126.340	+INF	
R23		179.660	+INF	
R24		1635.560	+INF	.
R25		1402.400	+INF	.
R26	.	261.440	+INF	.
R27	.	45.500	+INF	.
R28	.	158.180	+INF	.
R29	.	18.200	+INF	.
R30		10.360	+INF	.
R31		1400.440	+INF	
R32		341.960	+INF	
R33		144.460	+INF	.
R34	.	.	+INF	5.600
R35	.	207.380	+INF	.
R36	.	.	+INF	11.200
R37	.	197.440	+INF	
R38	.	27.240	+INF	
R39		251.500	+INF	
R40		99.560	+INF	.
R41		.	+INF	5.600
R42		33.570	+INF	

R43	225.160	+INF	.
R44	331.720	+INF	.
R45	9.520	+INF	
R46	458.040	+INF	.
R47	47.600	+INF	.
R48	28.140	+INF	.
R49	27.300	+INF	.
R50	98.300	+INF	

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR TOTCOST	-INF	4.7652E+5	+INF	

---- 470 VARIABLE XT.L shipment of wood residues among regions

	R1	R2	R3	R5	R7	R11
R1	438.610					
R2		1448.780				
R3		272.420	250.000			
R5				250.000		
R7	456.330				59.550	
R8		278.800				
R11						250.000
R14					190.450	

+	R12	R14	R17	R18	R19	R22
R12	250.000					
R14		52.560				
R17			36.500	399.500		
R18				38.500		
R19					250.000	
R22						62.000

+	R24	R25	R31	R34	R36	R41
R24	250.000					
R25		250.000				
R28					60.820	
R31			250.000			
R33						105.780
R34				28.560		
R36					189.180	
R41						144.220
R42				226.940		

```
+       R42
R42   19.250


---- 470 VARIABLE  ZT.L   shipment of forest residues among regions

          R1
R1     5.060


**** FILE SUMMARY

INPUT       C:\ACADEM\GAMS-W\LPMOD.GMS
OUTPUT      C:\ACADEM\GAMS-W\LPMOD.LST
```

APPENDIX D

MODIFIED LP MODEL: A TRANSPORTATION PROBLEM PROGRAM AND RESULTS (OUTPUT OF NEW DEMAND SCENARIO)

GAMS 2.25.064 386/486 DOS 02/07/96 11:11:10 PAGE 1
LP MODEL: A TRANSPORTATION PROBLEM (LPNEW,SEQ=1)

* The LP model for Base Case program is slightly modified to develop a new demand scenario. The new demand quatity is added in Region 27 as shown below while the rest of the program is exactly as the base run model. This program file is saved under *LPNEW.GMS* name.

```
121     Y(J)  quantity demanded in regions in thousand tons
122     /  R1    900.00
123        R2   2000.00

 .
148        R27  1000.00


170        R49     0
171        R50     0    / ;
```

RESULTS (OUTPUT OF NEW DEMAND SCENARIO)

```
---- EQU DEMAND    quantities demanded in region J
       LOWER      LEVEL      UPPER     MARGINAL
R1    900.000    900.000    900.000     22.000
R2   2000.000   2000.000   2000.000     10.800
R3    250.000    250.000    250.000     -6.000
R4       .          .          .        -6.000
R5    250.000    250.000    250.000    -11.600
R6       .          .          .        -6.000
R7    250.000    250.000    250.000     10.800
R8       .          .          .        -6.000
R9       .          .          .       -11.600
R10      .          .          .       -11.600
R11   250.000    250.000    250.000    -11.600
R12   250.000    250.000    250.000    -11.600
R13      .          .          .        -6.000
R14    52.560     52.560     52.560     -6.000
```

R15			.	-6.000
R16	.	.	.	-6.000
R17	36.500	36.500	36.500	-17.200
R18	438.000	438.000	438.000	-6.000
R19	250.000	250.000	250.000	-11.600
R20			.	-17.200
R21	.	.	.	-17.200
R22	62.000	62.000	62.000	-17.200
R23	.	.	.	-17.200
R24	250.000	250.000	250.000	-6.000
R25	250.000	250.000	250.000	-0.400
R26	.	.	.	-6.000
R27	**1000.000**	**1000.000**	**1000.000**	**5.200**
R28			.	-6.000
.				
R49				-17.200
R50				-17.200

---- VAR XL quantity of wood residues landfilled in region I

	LOWER	LEVEL	UPPER	MARGINAL
R1			+INF	33.600
R2			+INF	16.800
R3		142.870	+INF	
R4	.	2810.760	+INF	
R5	.	742.380	+INF	
R6	.	1569.480	+INF	
R7	.		+INF	16.800
R8			+INF	5.600
R9		171.400	+INF	
R10		317.720	+INF	
R11		1806.660	+INF	
R12		182.000	+INF	
R13		432.000	+INF	
R14		354.870	+INF	
R15	.	729.420	+INF	
R16	.	537.580	+INF	
R17	.	556.400	+INF	.
R18	.		+INF	11.200
R19		799.400	+INF	
R20		0.840	+INF	
R21		81.360	+INF	
R22		126.340	+INF	

R23		179.660	+INF	
R24		1635.560	+INF	
R25		1402.400	+INF	
R26			+INF	11.200
R27			+INF	22.400
R28			+INF	11.200
R29		.	+INF	EPS
R30		10.360	+INF	
R31	.	1400.440	+INF	
R32	.	341.960	+INF	
R33	.	244.020	+INF	
R34			+INF	5.600
R35			+INF	11.200
R36			+INF	11.200
R37		.	+INF	EPS
R38	.	27.240	+INF	
R39	.	251.500	+INF	
R40	.		+INF	EPS
R41	.	.	+INF	5.600
R42		33.570	+INF	
R43		225.160	+INF	
R44	.	331.720	+INF	.
R45	.	.	+INF	5.600
R46	.	458.040	+INF	
R47		47.600	+INF	
R48		28.140	+INF	
R49		27.300	+INF	
R50		98.300	+INF	

---- 470 VARIABLE XT.L shipment of wood residues among regions

	R1	R2	R3	R5	R7	R11
R1	438.610					
R2		1448.780				
R3		462.870	250.000			
R5				250.000		
R7	456.330				59.550	
R8		88.350			190.450	
R11						250.000

+	R12	R14	R17	R18	R19	R22
R12	250.000					
R14		52.560				
R17			36.500	399.500		
R18				38.500		
R19					250.000	
R22						62.000

+	R24	R25	R27	R31	R34	R36
R16			102.340			
R24	250.000					
R25		250.000				
R26			261.440			
R27			45.500			
R28			219.000			
R29			18.200			
R31				250.000		
R34					28.560	
R35			207.380			
R36			136.620			52.560
R37						197.440
R42					226.940	
R45			9.520			

+	R41	R42
R33	6.220	
R40	99.560	
R41	144.220	
R42		19.250

--- 470 VARIABLE ZT.L shipment of forest residues among regions

	R1
R1	5.060

EXECUTION TIME = 1.640 SECONDS VERID MW2-00-064

**** FILE SUMMARY
INPUT C:\ACADEM\GAMS-W\LPNEW.GMS
OUTPUT C:\ACADEM\GAMS-W\LPNEW.LST

APPENDIX E

GLOSSARY

Base Run Case: This relates to the existing or current situation of price (cost), demand and supply for the product in the study while new scenario case includes potential changes in price, demand or supply.

Constraint: Usually this is a relation of the form of an inequality, $g(x)<=0$, or equation, $h(x)=0$. More generally, it can be any restriction the decision variables must satisfy. For example, some regard "x must be integer-valued" as a constraint, while others would say that this is simply the domain of the decision variables in the mathematical program. There are other relations, such as the logical form of a precedence constraint: IF $x=0$ THEN $y=0$.

Demand: In this study, this means the amount of wood residues in tons required by wood burning power plant.

Inputs: A term used for the amounts of the various factors of production employed by a producer.

Linear Program (LP): A mathematical method of determining an optimal combination of inputs to maximize (or minimize) profit (or cost) with an objective in which the input variables are subject to constraint.

Optimize $\{cx: Ax = b, x>=0\}$. (Other forms of the constraints are possible, such as, $Ax <= b$.) The standard form assumes A has full row rank. Computer systems ensure this by having a logical variable (y) augmented, so the form appears as Optimize $\{cx: Ax + y = b, L <= (x,y) <= U\}$ (also allowing general bounds on the variables). The original variables (x) are called structural. Note that each logical variable can be a slack, surplus, or artificial variable, depending on the form of the original constraint. This computer form also represents a range constraint with simple bounds on the logical variable. Some bounds can be infinite, and a free variable (logical or structural) is when both of its bounds are infinite.

Marginal Cost: The extra cost of increasing output by one more unit. Thus if it costs $110 to produce 50 units of a commodity and $112 to produce 51 units, marginal cost is $2. If marginal cost is falling production will be under conditions of increasing returns, whereas if marginal cost is increasing production will be subject to diminishing returns.

Maximand: Upper limit of an objective function.

Objective Function: The (real-valued) function to be optimized. In a mathematical program in standard form, this is denoted by f.

Output: In LP, this simply means the result of the model. While in economic term, this is a good or product produced by a producer (company). One of the assumptions of economics that every producer will aim at producing that output that will yield him maximum profit.

Parameter: A constant in a mathematical program, not subject to choice in the decision problem, but one that could vary outside the control of the decisions. Examples are supplies, demands, loss factors, exponents and coefficients in polynomial functions (of the decision variables). Not all coefficients are parameters, as many are zero by the logic of the model. For example, the only data for a standard transportation problem are the costs, supplies and demands. These can depend upon parameters, but the LP matrix does not -- it is the incidence matrix of the network. In general, parameters are data-dependent constants, rather than logically fixed for all instances of the model. Some parameters are simply units of measurement, such as the amount of energy (Btu) in a ton of coal, whereas some parameters are uncertain, like demand for a product.

Secondary Wood Manufacturer: This includes the Wood Manufacturing Companies such as: Millwork, Cabinet and Furniture, Boxes and Containers. For this study purpose, based on number of employee, these companies are sub-grouped into:
(a) Large with >20 ; and (b) Small with <20 employees.

Sensitivity Analysis: This is an analytical technique to test systematically what happens to the result (project outcome) if the prices, demands, or supplies change in future. These changes are incorporated in the analysis usually one at a time and project its impact on the result of the project.

Shadow Price: An economic term to denote the rate at which the optimal value changes with respect to a change in some constraint (right-hand side) that represents a resource supply or demand requirement. For intermediate goods and services, the shadow price is the opportunity cost, the benefit forgone by using scarce resource for one purpose instead of its nest best alternative use.

Supply: In this LP study, supply of wood residues means the amount available at wood manufacturing companies and can be supplied to wood burning plant or any other uses.

Transportation Problem: Find a flow of least cost that ships from supply sources to consumer destinations. This is a bipartite network, N = [S * T, A], where S is the set of sources, T is the set of destinations, and A is the set of arcs. In the standard form, N is bi-complete (A contains all arcs from S to T), but in practice networks tend to be sparsely linked. Let c(i,j) be the unit cost of flow from i in S to j in T, s(i) = supply at i-th source, and d(j) = demand at j-th destination. Then, the problem is the linear program (LP):

Minimize Sum_ij {c(i,j) x(i,j): i in S, j in T}: x >= 0,

Sum_j {x(i,j): j in T} <= s(i) for all i in S;

Sum_i {x(i,j): i in S} >= d(j) for all j in T.

The decision variables (x) are called flows, and the two classes of constraints are called supply limits and demand requirements, respectively.

Variable: This is an entity which can take any value unless specified.