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HARVESTING OF CLOSE-SPACED SHORT-ROTATION WOODY BIOMASS

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MASTER

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I. INTRODUCTION

A. Background

The goal of the woody biomass energy plantation is to efficiently produce annually a quantity of biomass suitable for conversion to one or more energy products for use in the U.S. economy. Exploratory studies have indicated that hardwood trees are a particularly attractive type of vegetation for conversion of solar energy when coupled with proper species selections and intensive cultivation on biomass farms. Preliminary results have revealed the advantages of employing short-rotation plantations to take advantage of the greater productivity of juvenile trees. Further advantages can be achieved through utilizing a fast growing species that permits close-spaced planting to provide a large number of stems per acre and by selecting a species capable of regeneration by coppicing from stumps. Tree plantations for energy, as such, do not currently exist. Although considerable attention has been directed at evaluating the merits of various candidate species, the selection and preparation of sites, and the management technique to be applied, little effort has been focused on the harvesting, collecting, transporting and storage of the woody biomass. The latter constitutes the link between the tree growing and the wood conversion systems. The objective of this project within the Fuels from Woody Biomass Program is to investigate alternative strategies and techniques of harvesting which appear to be commercially viable for use on closely spaced short-rotation biomass farms where coppicing will be used.

Efforts to date have been concerned with identifying the characteristics of prospective woody biomass farms; the requirements for harvested wood to provide feedstock for various conversion processes (see Appendix I); the characteristics of harvesting, collecting, transporting, and storing equipment as used by the forest products and agriculture industries; the applicability of the foregoing equipment to close-spaced, short-rotation biomass farms; and the modelling of alternative systems linking biomass farms and biomass conversion plants. These models can achieve the lowest cost system by application of optimization techniques.

Chemical and mechanical engineering studies in recent years have focused on the conversion of woody biomass to energy related products to supplement those derived from conventional fossil resources. Harvested wood has been mechanically chipped or pulverized to provide a fuel for direct combustion or chemically converted by processes such as pyrolysis and partial oxidation to produce liquid or gaseous energy related reaction products. The chemical conversion of course, involves rearranging the molecular structure of woody biomass while the mechanical conversion methods simply involve, for the most part, subdividing the biomass plus water removal. The products of the chemical conversion may constitute intermediate products which are to be further used in formulating or synthesizing other energy related products. For example, the carbon monoxide and hydrogen resulting from partial oxidation constitute the building blocks for virtually an unlimited range of organic products.

The energy related products that are primarily prepared by conversion of the wood are electricity through the heat of combustion of the biomass, charcoal as a product of combustion, energy containing fuel gases through partial combustion of the wood feedstock and process heat. In addition, energy containing liquid fuels such as methanol, ethanol, and ammonia are readily available from woody biomass by well-known process engineering technologies. The total array of all possible products is imposing. Instead of attempting to categorize them sufficiently well to establish criteria for raw material feedstock requirements, it is more important for our purposes to identify the conversion processes. A number of the products can, of course, be made by alternative processes which constitutes no difficulties in the methodology for analyzing the raw material-to-end product system. Further, a small number of the products are made in a form which does not lend itself to marketing owing to prohibitive distribution costs of transportation. Virtually all conversion processes, particularly at large-scale, operate more efficiently with finely divided wood, mainly because of the increased surface to volume ratio of the wood particle and also as a result of the fluidized handling characteristics of the finely divided mass of material. Those that are exceptions consist of a segment of the charcoal industry which utilizes chips as large as three inches for feedstock and wood used for steam boiler fuel. The latter's characteristics involve a trade-off between achieving high rates of combustion per unit volume of the combustion zone with fine particulate wood and loss of unburned fuel swept out the stack owing to high air velocities. By employing wood chips in the regions below 2 inch size (20% through a 1/4 inch mesh) investigators have found a higher Btu release per ton of input fuel is achieved than with finely divided wood owing to reduced unburned fuel losses. Low moisture content of chips is also beneficial. Tests with a 10 megawatt generator driven by an 850 psi boiler fired with 8 to 9 tons per hour of wood chips have also shown that where chips with 38% to 45% moisture content will develop 6.5 megawatts, the chips, when reduced to a moisture content of 22% to 26%, will produce 8 to 8.5 megawatts.[1]

Wood feedstock for charcoal production is quite flexible as to form and will range from sawdust size to 3 inch green chips. The chips are generally dried by waste heat recovery from the process combustion gases. The charcoal output from a charcoal process such as the Nichols-Herreshoff Multiple Hearth Process in Belle Mead, New Jersey, will be particles in the range of .05 to 2.0 millimeters. In essence charcoal is a synthetic coal produced from a renewable resource. Production yields from wood of this fuel are about 30% by weight of wood (air-dried) with heat contents of 13,700-14,000 Btu per pound. Accompanying the charcoal production is also a liquid fuel oil or a low Btu fuel gas.

There are a number of liquid fuel products obtainable from wood either by utilizing pyrolysis or by employing a liquid reaction system. The latter generally involves the action of a steam-acid solution on the wood biomass or a bacterial process or an enzymatic action to break down the cellulose molecules of the wood. In all such processes, finely divided wood particles are preferred in order to provide intimate contact of wood fibers and reactants with consequent rapid reaction rates and high yields.

The existing processing facilities designed to convert biomass are generally equipped to pre-process the wood feedstock to the precise form required by the individual process. Consequently the wood biomass inventory can be stored at the facility in any reasonable form that is economically and technically acceptable for its later use. Typical of these facilities are the paper mills which have installed de-barkers and chippers to handle incoming pulpwood as well as wood chips supplied by vendors.

The biomass plantation in general presents more flexibility as regards harvesting than does the biomass conversion plant relative to storage. The short rotation growing stock on hardwood tree farms in southeast U.S. will average well below 4 inches diameter at ground level after 5 years and for the most part will be of the order of 1-1/2 inch diameter at 3 years. Although the physical characteristics of this size tree are not comparable to any agricultural crop (other than sugar cane) nor to any conventional forest stands, they are sufficiently close to both to apply extrapolated technology from grain and woodlands operations to the harvesting of close-spaced, short-rotation woody biomass. The technology and practices used in sugar cane harvesting are in particular closely allied to those needed for juvenile trees.

The harvesting process entails clear-cutting small diameter trees close to ground level to maximize the yield while simultaneously preventing the inflicting of permanent damage to the root structure. Further this process must be carried out economically and at a rate that will sustain the requirements of the end-using conversion facility.

In conjunction with the tree cutting, a process of collection of the woody biomass is employed to facilitate the eventual transporting of the material to a place of storage. The cut stems can be banked or windrowed on the ground adjacent to their stumps for subsequent loading in a transportation vehicle or they can be continuously loaded in a vehicle accompanying the cutter after some preliminary chopping of the stem to facilitate loading and packing. Agricultural practices will vary with specific crops. Frequently windrowing of crops is practiced. Also cutting and processing the crop in a combined operation is often employed as in soybean harvesting. In this case the soybeans are transported in field by the harvester to a highway vehicle for further movement to a central storing area or to a processing plant. Such crops as sugar cane use a wide spectrum of harvesting practices generally associated with a broad range of environmental, geographical, and social conditions under which it is grown. These conditions are sufficiently diverse that the cane harvesting machinery is designed to fit specific growing areas of the world. In keeping with the need for harvesting for fuel large quantities of woody biomass, the sugar cane industry has also recognized in their business the advantages of handling large volumes of growing material. A single machine harvester can adequately cut 50 to 60 tons per hour on a continuous basis if the land is free of rocks, debris and other obstructions with evenly spaced rows at proper intervals and with the terrain virtually level between rows. In addition, adequate areas at the end of each row are needed to provide rapid turning of the harvesting and transporting vehicles. Machine harvesting and collecting have been merged in some machine design into a closely coordinated operation by virtue of utilizing a fleet of tractors and wagons to accompany the harvester through the fields. Handcut cane is windrowed and later collected and loaded by a continuous loader. Several machine harvesters also utilize this approach using a cutter windrower with a second machine to lift, chop, and clean the windrow.

Woodlands harvesting in the forest products industries is focussed on shearing trees generally above 6 inch diameter (dbh) for use as lumber, pulpwood, or plywood. Both hand and machine felling of trees is employed. The modern feller-buncher and delimber and associated skidders and loaders have mechanized to a high degree the harvesting of intermediate size trees. For the cutting of trees for use in wood pulp, the mobile chip harvester has improved the mechanization of woodlands operation, particularly for the production of whole tree chips. The limitations on equipment usage in forestry are essentially due to the massive size of very large diameter trees or the small diameter trees which are of little importance in the lumber, pulpwood, and plywood industries. Additional constraints on woodlands practices in harvesting are the mechanical limitations on using conventional equipment to cut and collect small diameter trees. The engineering designs employed in developing equipment for felling, bunching, accumulating, and skidding large trees and large diameter logs have resulted in machinery which is not directly applicable to harvesting close-spaced, small diameter trees.

B. Approach

An assessment has been made of the feasible systems of harvesting, collecting, transporting and storing to link the supply of wood biomass of the tree plantation and the consumption needs of the conversion facility. A number of alternative systems have been conceived and compared with competitive options. Since no system currently exists and is operative, the conceptualization of various operations was performed based on the functions necessary to provide the conversion activities with the biomass feedstock in the quantities needed on a timely basis. It has been assumed that a consistent quality of wood feedstock will be produced on the managed tree farms but not necessarily a monoculture operation.

The composition of the woody biomass relative to such characteristics as moisture content (Table) rather than its fiber content or structural strength are of interest in the conversion to an energy product. Further, for typical saw-timber stands, some 65% of the tree by weight is in the main stem while saplings may have less than 55%. Consequently, it is desirable to utilize as much of the short-rotation tree as can be economically captured. To this end, the harvesting operations are focussed on utilizing 100% of the tree consistent with maintaining the safety of the coppicing activity of the stump.

The feasible systems are composed in general of two major parts each of which was visualized as essential to the harvesting program. An array of transportation materials and storage depots constitute one segment and the characteristics of the equipment, performance, and the number of machines the other. The objective is as follows: given a tree farm of a particular area and configuration from which a specific quantity of woody biomass is to be cut daily, what combination of types and numbers of equipment and transportation network will provide the minimum cost operation to deliver and store wood at the prescribed site of a conversion plant.

The group of transportation networks has been formulated based on considering the practical aspects of grain and cane harvesting and those problems involved in cutting and transporting trees in woodland operations. The networks involve such routings as field transporting and in-field storage, secondary road hauling and storing, and highway trucking to plant site and storage as well as various combinations of these.

The equipment characteristics and performance to accomplish the harvesting of the short-rotation tree crop is based on a compromise between that which would appear to be required and that which can be commercially obtained by virtue of extrapolating agriculture and forest products equipment characteristics and performance. The extrapolation is extended to all aspects of the machinery, including initial cost, operating cost, maintenance, operating life, and performance under various types of soil, terrain, and weather. A number of machines are also considered which are used by neither agricultural nor forest harvesting operations. These are primarily the types of equipment that relate to compacting and aggregating bulk materials and could presumably be used to bale several trees and the chopped or chipped segments of these trees.

II. DESCRIPTION OF CUTTING-COLLECTING-TRANSPORTING-STORAGE SYSTEMS

A. General

The development of a commercially acceptable system to harvest and move the biomass material to the conversion plant site involves trading off the advantages to be gained by utilizing effective methods against the associated disadvantages both economical and technical incurred in applying these methods. In order to cost optimize the system, a number of techniques and methods have been explored which lend themselves to being implemented under a wide range of environmental conditions, on various types of soil and terrain, and utilizing standard agricultural or woodlands harvesting equipment modified sufficiently to be applicable to juvenile trees. For the most part, the systems conceived reflect the general specifications that can be established for harvesting this woody biomass, namely:

- Large quantities of material harvested per day
- Low operating and investment costs per ton of material handled
- Minimal damages to the root structure and tree stump
- Evaluated and controlled environmental effects on run-off, debris accumulation and wildlife
- Harvested material stored in the field, at staging areas, and at the conversion plant site
- Sustained operation of system on a continuous basis

In addition, these general specifications imply further constraints owing to the interaction of the function of shearing, collecting, transporting, and storing and the equipment utilized to fulfill the functional requirements. For example, minimizing root structure and stump damage may preclude more than one passage of cutting and collecting equipment through the tree farm.

All such interactions and constraints have been considered here in constructing the total system and associated models. The options that are available and feasible have been developed together with their costs. Existing information on equipment already being used commercially in harvesting various crops has been used to arrive at minimal values for the performance characteristics of proposed young tree harvesting. Primary among these are agricultural crop equipment such as those used in cereal grain and corn harvesting, sugar cane harvesting machines, and conventional forest harvesting equipment.

B. Agriculture Harvesting

Agriculture grain harvesters are an evolutionary development that has taken place over the past 150 years and has culminated in the modern combine. Today's machine is a system which combines favorable working conditions for the operator, a high rate of production, low field loss of crops, low processing loss, undamaged grain, long service life, low maintenance, low manpower requirements for operating, low operating cost, and the economies of scale accompanying a large piece of equipment. Implicit in the optimum designs of today's self-propelled machine is a capability to unload the harvested grain stored within the machine tank in a matter of minutes (two bushels/second), discharge and spread the crop residue in a prescribed pattern, and operate effectively under adverse conditions such as soft fields or rough terrain. In addition, a high degree of flexibility in header attachments is incorporated to permit handling a range of crops. Typical of the large efficient combine is the International Harvester Model 915. This machine will cut up to a 24-foot width of crop at a rate of approximately 2-1/2 to 3 mph. This is harvesting in the neighborhood of 700 bushels per hour or about 20 tons of grain or beans per hour. Virtually an equal weight of material in the form of crop residue is also processed and ejected by the equipment. Consequently, approximately 40 tons per hour of material is handled.

A second type of agricultural machinery used in harvesting is the forage equipment. These machines are designed to cut and collect corn stalks, to pick up windrowed hay, or to direct cut forage crops in large volumes at high performance rates. By utilizing gathering heads to span as many as 4 field rows of corn stalks, a large forage harvester, for example, will cut 100 tons per hour from a site yielding 10 tons per acre of corn stalks. The length of cut produced by this equipment will generally range from 1/4 inch to 1/2 inch. By synchronizing feed and cutting speeds, a high rate of cutting and chopping can be obtained for any selected length of cut. This high productivity requires substantial horsepower capability in the equipment. A large Deere Model 3800 pull-type forage harvester will require a 155 hp tractor while a self-propelled Deere unit, Model SP5460, will involve a 255 hp engine for power.

These harvesters are produced with 28 to 30 inch and 36 to 40 inch row heads and are capable of shearing off corn stalks within inches of the ground surface. This equipment is designed to gather, simultaneously, multiple rows of corn stalks and feed them individually by means of a rubber belt and auger to the centrally located cutter for chopping to a prescribed length. The stalks are sheared off by an oscillating knife as they are grasped by the rubber belt. Cutting is achieved with a high speed cylinder on which are mounted a number of knives somewhat similar to a reel lawnmower. With, for example, a harvester equipped with a 1000 rpm cylinder on which 9 knives are mounted plus a requirement for 1/2 inch length fodder, a belt mechanism will feed stalks at a prescribed rate of 6.2 feet per second in order to obtain the required lengths.

The high rate of production of the forage harvester requires several wagons to accompany the cutter in the field to receive the cut material for transportation. These wagons will store in the range of 500-700 cubic feet of material and incorporate rapid unloading features to expedite the round trip time from harvester to storage area. Cut material can be mechanically ejected from the wagon or by means of a tractor blower attachment it can be permanently blown into a storage ditch or building.

Virtually all forage harvesters are designed along identical principals, namely a header is utilized to gather in the stalks, a cutter shears off the stalk at base, a conveying belt or chain feeds the material to an auger which moves the stalk laterally to a position at the cutter, moving rolls feed the positioned stalk into the cutting knives, the cutting knives cut the stalk to a prescribed length dictated by the feed rolls and speed of revolution of the knives, and a blower or conveyor deposits the chopped material in a storage compartment. Variations between designs occur in such areas as number of knives mounted on the rotating cylinders, speed of revolution of the cylinder, diameter of the cylinder, and engine horsepower. Other variations of secondary importance in standard agricultural harvesting but capable of assuming a primary role in wood harvesting are: axle height clearances, tire size, and ease of operation. Adequate clearance between the harvesting machine and the ground is vital in traveling over stumps in order that no damage occur and no subsequent impairment of the coppicing function; tire size is relevant to flotation and the pressure on subsurface root structures of the young tree stumps; and ease of operation is of paramount importance in keeping damages to a minimum.

C. Wood Harvesting

The equipment for the harvesting of wood for the forest products industries has evolved from the early practices of exploiting material stands. For centuries, the use of wood in the populated temperate zones of the world was undertaken without regard for any long-term implication as to the future state of this natural resource. With the depleting of the stands in Europe several centuries ago, an attempt was made to undertake reforestation and the management of these forests with the objective of maintaining a perpetual supply of wood. The development of improved practices for growing and managing woodlands also contributed to better methods for harvesting. The search for more efficient cutting techniques to improve productivity resulted in power saws to replace hand saws and axes for harvesting trees of moderate dimensions. Subsequently, the feller with its power shears supplemented the chain saws as an economic improvement. Although the feller is limited both as to minimum and maximum size tree that can be handled, its speed of operation in shearing intermediate diameter trees is very favorable compared to earlier methods. By performing several mechanized operations virtually simultaneously, such as topping, delimbing, and shearing, a large powered tree harvester will cut at ground level a tree on the order of 18 inches in 5 seconds and then lift it (a weight of approximately 10,000 pounds) to a position for delimbing or to a bunching position for skidding to a location for further processing. An overall time to accomplish these operations can be as low as 1 minute for two 18 inch trees. Rates as high as 300 pine trees (15 inch diameter) per hour have been attained. The engineering design of such equipment has been tailored to permit access of the equipment to narrow passages in forests. In addition, it has an extended reach to permit selective cutting of adjoining trees. Additional developments in this equipment have resulted in equipment that will cut as well as accumulate a number of trees in the equipment prior to carrying them to a bunching point.

The effectiveness of the feller consists of its continuous operation in felling trees. In order to move large trees out of the area as they are harvested, a skidder or grapple is used to drag one or more trees simultaneously from the feller to the landing area. This vehicle is highly maneuverable and only a single operator is needed to pick up and transport the load. Generally this equipment is used for trees larger than 5 inch diameter. A typical load will be 1-1/2 cords (4 tons). Both the feller and the skidder will operate on sloping terrain in excess of 15^o. The skidder generally drags the fallen tree by means of an attached cable while the grapple grasps the tree in a boom clamp, lifts that end of the tree, and drags it from the forest. Under very adverse conditions of wet weather which prevent wheel or track vehicles from entering an area, trees are skidded to a loading area by means of a cable and winch.

Log fork equipment is also used in a number of loading applications. By means of double clamp attachments on a loader, a bundle of logs can be rapidly picked up in the woods or the millyard and loaded on a flat bed truck.

Since the introduction of mobile debarkers and chipping machinery, frequently the chips are transported in vans to the mill. Chippers are now available that will produce whole-tree chips coupled with a cleaning action. Owing to the tree being skidded over rough ground from the felling site to chipping area, there is generally dirt, sand, and mud attached. This non-merchantable material can be removed to some extent from the whole-tree chips by the advanced models of such equipment as the Chiparvestor. This machine will also handle whole trees with limbs intact. Chips can be produced in a size ranging from 5/8 inch to 1 inch. The equipment is designed to chip entire trees as well as brush and chunks of wood material after which the chips are discharged pneumatically. The introduction of efficient mobile chipping capability into this harvesting system has provided opportunities for transportation and purchasing economies. There is now flexibility in the system relative to debarking and chipping wood transported to the processing plant, or debarking and chipping in the field and trucking chips to the processing plant, or purchasing chips produced by suppliers in the field.

D. Sugarcane Harvesting

The growing and harvesting of sugarcane represents a segment of the agricultural industry whose characteristics and practices lie between conventional agriculture grain operations and the growing and harvesting of woodland crops in the forest products industry. In particular, sugarcane after harvesting will regenerate shoots (ratooning) similar to coppicing of hardwood trees. The cane is close-spaced, with a stalk diameter of the order of 5 cms. for fully grown cane and frequently reaches a height of 2.5 to 3.5 meters depending upon latitude, spaces, and climate. The cane is a tough grass with a consistency of the order of wood and a resistance to cutting comparable to that of young trees. The fully developed crop produces a top and foliage which results in a heavy accumulation of debris or trash both on the cane and on the ground somewhat atypical of both grain crops and woodlands. This vegetation is removed generally by preharvest burning as it has been found that this unburned fibrous material - trash - during milling introduces a higher net amount of fibrous cane material (120% additional) and requires 0.16 kwh per ton more energy accompanied by a decreased grinding rate. Further, the cane cutter's productivity is increased as much as 39% and the utilization of transporting facilities is increased about 28% when field burning is performed. In addition it is reported that preharvest burning reduces sugarcane field losses in machine harvesting and more than doubles harvester capacity per hour. However there appear to be trade-offs inherent in employing the burning of "trash". In South Africa it has been observed that trash from green cane (unburned) serves to conserve soil moisture and improves sugar production.

However, in Australia and Florida, for example, such benefits are not apparent and the presence of trash has little relevance to sugarcane culture. The influence of large quantities of sugarcane leaf trash and tops on subsequent ratoon crops has not been evaluated.

Investigations have focused generally on the relationship of trash to milling and sugar recovery rather than crop productivity and harvesting. Among the adverse effects accompanying the physical presence of trash are the undesirable characteristics of dry trash to absorb juice during grinding of the cane then carrying away non-recoverable sucrose and the tendency of green trash to introduce quantities of impurities into the cane juice. In addition if preharvest burning is to be performed, the field layouts must include adequate fire lanes to confine fires to individual fields. The acreage burned results in accelerated sugar losses. Consequently only that area is burned that can daily be cut, collected, loaded, transported and milled.

In summary, the technology of sugarcane harvesting consists of employing methods that have advantageous as well as adverse effects on the growing, cutting, collecting, transporting, storing, milling and classifying processes of sugar production. By judicious trade-offs involving equipment and practices and giving the necessary consideration to the climate, weather and variety of cane it has been possible for growers to move toward an optimized technique of growing and producing this crop. This is a commendable approach in view of sugarcane's per acre per year tonnage processed exceeding that of all other agricultural and forest crops.

Sugarcane in the U.S. is produced in 3 areas: Florida, Louisiana, and Texas. Each area utilizes techniques and practices adapted to that region. Approximately 1,600,000 tons of sugar per year is produced on some 750,000 acres. The yield of sugarcane is approximately 15 to 50 tons per acre exclusive of tops and leaves with a raw sugar yield of .1 to .13 tons per ton of cane. Some U.S. areas produce as high as 80 tons per acre. The yield of sugar is sensitive to the timeliness of the processing and the trash present. A delay in milling (grinding) plus excessive trash can produce a loss of 8 to 22 pounds of sugar per ton of cane. Because of the annual freeze and its deleterious effect on the cane, the harvest must be pursued even though the growth may not be mature. Consequently delays in the overall acreage harvest schedule cannot be tolerated and the need for reliable highly productive harvesting equipment is clear.

Historically sugarcane has been cut by hand owing to the availability and low cost of the labor and the lack of uniformity of the crop growth. Sugarcane has the undesirable qualities of becoming lodged or recumbent principally owing to wind and rain. In addition, the associated leaves and tops of the stalk are a sufficient barrier to expeditous cutting that frequently the standing field of cane is burned (weather permitting). The hand cut cane is cut off low to the ground and piled in windrows for later collecting and transporting by cart. If unburned prior to cutting, the piled cane is generally burned one day (or longer) later when the leaves are sufficiently dry. At the season's beginning, the tops and leaves (30% of the net cane weight) are too green to burn effectively while the cane is standing. After burning, the piles of cane are loaded into carts for movement to the processing plant. Chopping of the cane into short sections, e.g. 9 in., 12 in., 14 in., 18 in., may occur during loading or at the grinding plant. During the past 25 years a number of mechanical harvesters have been developed which serve to overcome the major problem of harvesting, namely lodged and recumbent cane, undesirable leaves and tops, the necessity for operating under adverse conditions of terrain and weather, and the need for high productivity to prevent deterioration and losses. (A heavy-duty cane harvester is able to cut 350 tons per day in fields as dense as 90 tons per acre.)

A typical U.S. sugarcane field may be from 100 to 1000 feet in length by approximately 100 to 150 feet in width and will be located in wet soil with approximately 60 inch annual rainfall. Each side of the field contains drainage ditches which can vary from widths of 3 to 4 feet and depths of 1 to 4 feet. At both ends of the field roadways approximately 25 feet wide are located for turning equipment as well as hauling cane from the field. The rows of cane are parallel to the drainage ditches. Secondary drains into the rows aid in providing drainage into the side ditches. The cane is planted in ridged rows with 6 foot spacing which provides approximately 16 to 24 rows in a typical field. A mechanical harvester will collect from 3 to 6 rows of cane and heap stalks across one row ridge for drying.

If sufficient clear weather permits, the cane leaves can be burned satisfactorily and no delay exists in transporting the cane to be milled. However, if rainy weather occurs, in order to maintain the harvesting schedule the cane will be milled with trash rather than field inventorying the cut cane until it can be burned. It is recognized that loss of recoverable sugar and reduction in milling capacity may result.

Early mechanized harvesters cut tops as well as the bottom of a cane stalk. A gathering unit designed to feed erect stalks into a topper cutter is mounted on the harvester. The circular 16 inch diameter rotating blade of the topper is adjustable from a height above ground of approximately 2 to 3 meters and rotates at about 1000 rpm. The severed tops, approximately 2 feet in length, are discarded. The bottom cutter of the harvester consists of two horizontal rotating discs each approximately 19 inches in diameter with equally spaced serrated projections of the order of 2 inches on the periphery. The discs overlap about 2 inches and the cutting projections are staggered. The mower discs which rotate at about 400 rpm are spaced to provide sufficient clearance for foreign objects such as stones, rocks, and metal pieces to pass through without heavy damage. The bottom cutters height above ground are usually capable of being varied from 9 to 20 inches. Sugarcane is generally cut off slightly below the ground surface and the cutter is designed to be tilted down several degrees to improve digging into the cane row surface. Wear is severe and resharpening of the blades is necessary after cutting approximately 1000 tons. This virtually implies daily maintenance since the harvester is capable of a 100 tons per hour rate.

In order to collect, feed, clean, and store the cut cane, a chain elevating conveyor is incorporated in the harvester together with devices for stripping the leaves. This conveyor is synchronized with the harvester ground speed in order to maintain a constant feeding density.

Since cleaning of the cane is a necessary operation, cane combines generally include leaf strippers consisting of rotating cylinders with stripping fingers mounted to comb downward on the cane as it is moved by the conveyor to a loading area at the rear of the combine. The leaves present a problem since they will wrap around the cylinders under certain conditions and also reduce stripping efficiency by wrapping onto the fingers.

Substantial progress has been made in recent years in mechanizing harvesting equipment. Present machines designed along lines described above are capable of cutting and collecting has high as 100 tons per hour depending upon ground conditions and transport efficiency. It is difficult, for example, to achieve high output in fields that have been cultivated for manual cutting owing to residual rocks, debris, and other obstructions. For optimum productivity of a harvester, the land must be substantially level between rows and on ridge tops and the land at the head of the rows must be of sufficient size to allow rapid turning of the harvester and transport vehicles. The ridge tops should be less than 14 inches in height. The elimination of field cross drains is also necessary to prevent any obstructing of harvester and transport vehicle movements. A complete harvester system requires that adequate transporting of the cut cane be available continuously while the harvester is operating in order that high daily output be maintained. Under such favorable conditions a single unit will cut on a single 8 hour shift basis 20,000 tons (metric) of cane in a 20 week harvest season. This level of production with burnt cane can be obtained at cane densities ranging from 9 to 90 tons per acre with field leavings close to 1%. For green cane harvesting, productivity will be reduced by at least half. The current harvesters cut the cane, clean and eject the trash, grass, and weeds after which it is chopped into uniform billets approximately one foot in length.

Harvester adjustments on transmission, gatherers, lifters, cutting discs, feed rollers, choppers, and blowers provide for various conditions of terrain, debris, and cane billet length required. The latter generally range from 8 in. to 18 in.

The mechanical sugarcane harvesting is not without problems. The primary ones consist of large amounts of tops and leaf trash in the cut cane, uprooting of cane during harvest, and poor flotation of the heavy equipment on certain types of soil, particularly in Florida. Further difficulties surround the position of the cane stalks. About 25% of the stalks are upright in a position suitable for mechanically topping the stalk. For the remainder owing to a recumbent or semi-recumbent position, the mechanical topper has to be adjusted to compensate for the lower height. This places a heavy time premium on a harvester operator to be able to rapidly adjust topper height without reducing productivity. In general, the mechanical topper is not used where the cane stalks are not erect.

In soils that are soft the root system frequently will not be supported while the cane stalk is gathered into the harvester. Consequently the stalks are cut from the ground and are lifted into the harvester. Relatively flat terrain and cultivated areas are required for the harvester and transport vehicles to pick up the stalks. Both track vehicles and wide-tire wheel vehicles are used. The latter appear to be detrimental to the cane stubble owing to repeated trips to the field which involve the wide tires running over the stubble.

An additional problem that exists in mechanical sugarcane harvesting is the incidence of fires in the dry areas around the roots. Hand cutting followed by water wagon units moving between the rows appears to be better able to extinguish fires than mechanical cutters requiring an extra day to cut a field accompanied by an undesirable extra day of burning. It is not expected that this problem will exist in harvesting close-spaced short-rotation woody biomass since these fields would not be burned.

Mechanical harvesters generally cut one row and load at the rate of about 60 tons per hour. The hand cutter plus the continuous loader which takes 4 rows simultaneously loads at about 300 tons per hour. For a mechanical operation scaled to a rate of 1000 tons per day, additional transportation equipment is needed for the harvesters owing to the extended loading time. For low tonnage fields the transport time will be increased and also for small fields where many rows are traversed and therefore more turning time is required. Estimates made in Florida sugarcane fields indicate about 20% more field transport equipment is needed with the average mechanical harvester operation.

In general, the mechanical harvester has been found to be most effective if the following conditions and characteristics prevail:

1. Fields are smooth.
2. Rows are long and uniform.
3. Turning areas are made uniform and large enough to accomodate rapid turning.
4. The variety of growth is uniform.
5. The harvesters are grouped into larger units and production is scheduled by the mills.

6. In light tonnage fields the cut cane is loaded into transport vehicles at the time of cutting.

7. The fields must be sufficiently free of ground trash in order that the view of the harvester operator is not blocked. (Poor visibility prevents aligning the machine with the row and properly adjusting the cutter.) Further, any substantial quantity of trash accumulates in the equipment frequently choking feeders and conveyors. Finally, trash drastically reduces the capacities of both harvester and transport vehicles.

The growing of sugarcane varies greatly between such areas as Florida, Louisiana, Texas, and Hawaii. These variations, coupled with local differences in soil and terrain, are sufficiently large that each area has harvesters adapted to that region. In Hawaii the harvester must work under all weather conditions around the clock on steep slopes. Field stones and volcanic soil are a problem as they damage cutting knives. Consequently attachments (pushrakes) are used to reduce potential damage. The harvester itself is a very heavy duty piece of equipment weighing twice that used in Louisiana cane fields.

It appears likely that no single biomass harvesting machine will be suitable for all woody biomass forms envisioned. The cane harvesters are a close approximation of the equipment that will be needed since the short-rotation, close-spaced trees have many of the characteristics of mature sugarcane. Further, the high cutting collecting, loading, and transporting capacity of the sugarcane harvesting systems is also required for an effective woody biomass system. However, as was noted, no single harvester design has been found applicable to all sugarcane regions owing to significant differences in cane species and site environment. It is anticipated that a similar situation will exist for wood grown for fuel.

Basically, all agricultural and forestry systems for harvesting and growing crops involve the materials handling functions of cutting and accumulating, storing, collecting and processing, storing, loading and transporting, storing, and processing as shown in Figure 1. In a number of systems one or more operations may be modified and combined owing to the following:

- Characteristics of the crop involve both cutting and semi-processing in the field
- Dirt removal and field cleaning is essential
- Separating, classifying, and grading of the crop prior to storing is beneficial

The major differences between systems consist of the alternative types of sub-operation and equipment employed to fulfill each of the functions. Typical of these differences are those evident in the machine harvesting of such crops as peas removed from pods for processing and peas and pods intact for the fresh market. Windrowed pea vines are picked up by the combine and fed to a threshing machine which breaks open the pods releasing the peas. The latter are stored within the harvester and the separated pods and vines are discharged from the rear of the combine. Air blowers clean the peas of any debris and dirt.

For purposes of harvesting the total pod and peas for the fresh market it is desirable to have optimum density of the crop. This will vary with crop and variety; on most food crops the Agricultural Research Station of USDA can provide information as to row width and spacing of plants. There are, however, multi-density harvesters which will efficiently (90%-95%) harvest beans or peas in multi-density patterns or any row widths. Such equip-

Figure 1. Schematic Diagram of Material Flow

ment will handle three 36 inch crop rows, or six 18 inch rows, or eight 12 inch rows at the same speed and efficiency.

Consequently the harvesting system to be used for close-spaced short-rotation woody biomass will be a synthesis of those features and characteristics of the agricultural and forestry systems and equipment that can be transposed to the juvenile tree crop system. In addition, these would be supplemented by any operation that might be unique to handling woody biomass and also any environmental aspects that may constitute constraints on the system. The assembling of the data and steps in the formulation of the harvesting system are shown in Figure 2.

Ideally an integrated harvesting system should be developed that couples land and water resources, species of biomass, management strategies, harvesting systems, and feedstock for a fuel conversion plant. Presumably the best results could be obtained by optimizing this total system. At present it is premature to attempt to optimize the complete system to meet the demand for woody biomass at the lowest cost since the independent variables cannot be sufficiently well described analytically nor can the dependent variables be described precisely in terms of the independent variables and parameters. Consequently sub-optimizing of the major sections of the system is a more productive route in terms of securing practical results that can be readily and promptly applied to a fuels from biomass program.

III. SYSTEM DESIGN AND MODEL

The harvesting operation associated with supplying a single large wood conversion plant will be considered. The relationships

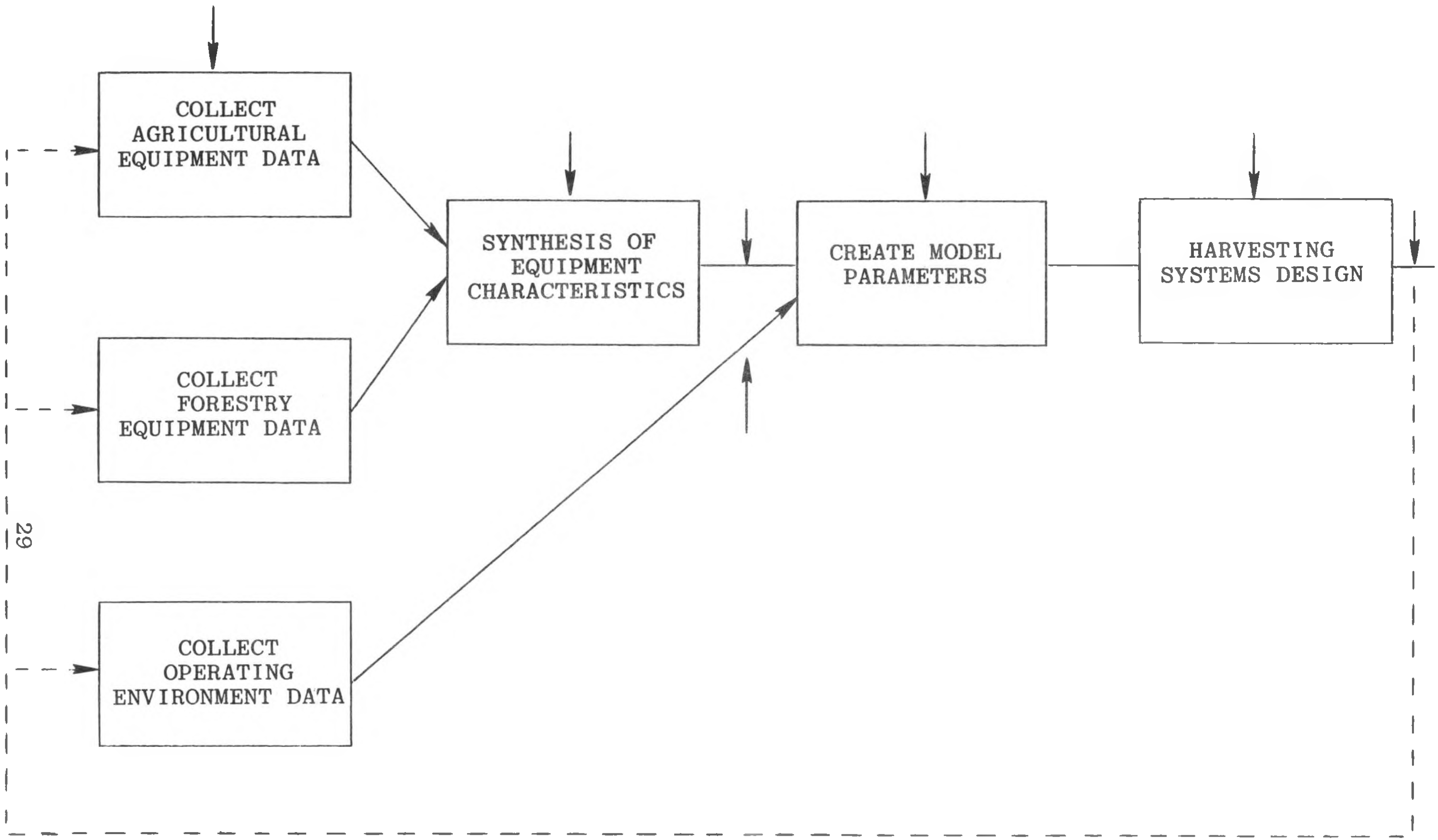


Figure 2. Data Assembly and Harvesting System Design

between the variables in this type of system are linear. Consequently by linear programming optimization techniques, a least cost solution can be obtained to the problem of meeting the conversion plant demands within the constraints imposed by the site, the equipment, and the operating procedures. This operation will consider alternatives consisting of:

- Number and types of equipment for:
  - Shearing
  - Chipping
  - Chopping
  - Collecting
  - Compacting
  - Pelletizing
  - Transporting
- Types of products supplied to plant
- Processing rates (volume per day)
- Transporting rates (volume per day)
- Modes of operation (speed of equipment)
- Site environmental conditions
- Time periods
- Distances from the plant site

The alternative harvesting sequences are diagrammed in Figure 3. There are other ways of presenting this information which more directly assist in developing and clarifying the optimization model. Figure 4 diagrams the possible sequence of activities with paths reconverging after each alternative.

Since some of the less likely sequences of processing and storing can be eliminated, this diagram has been simplified as shown

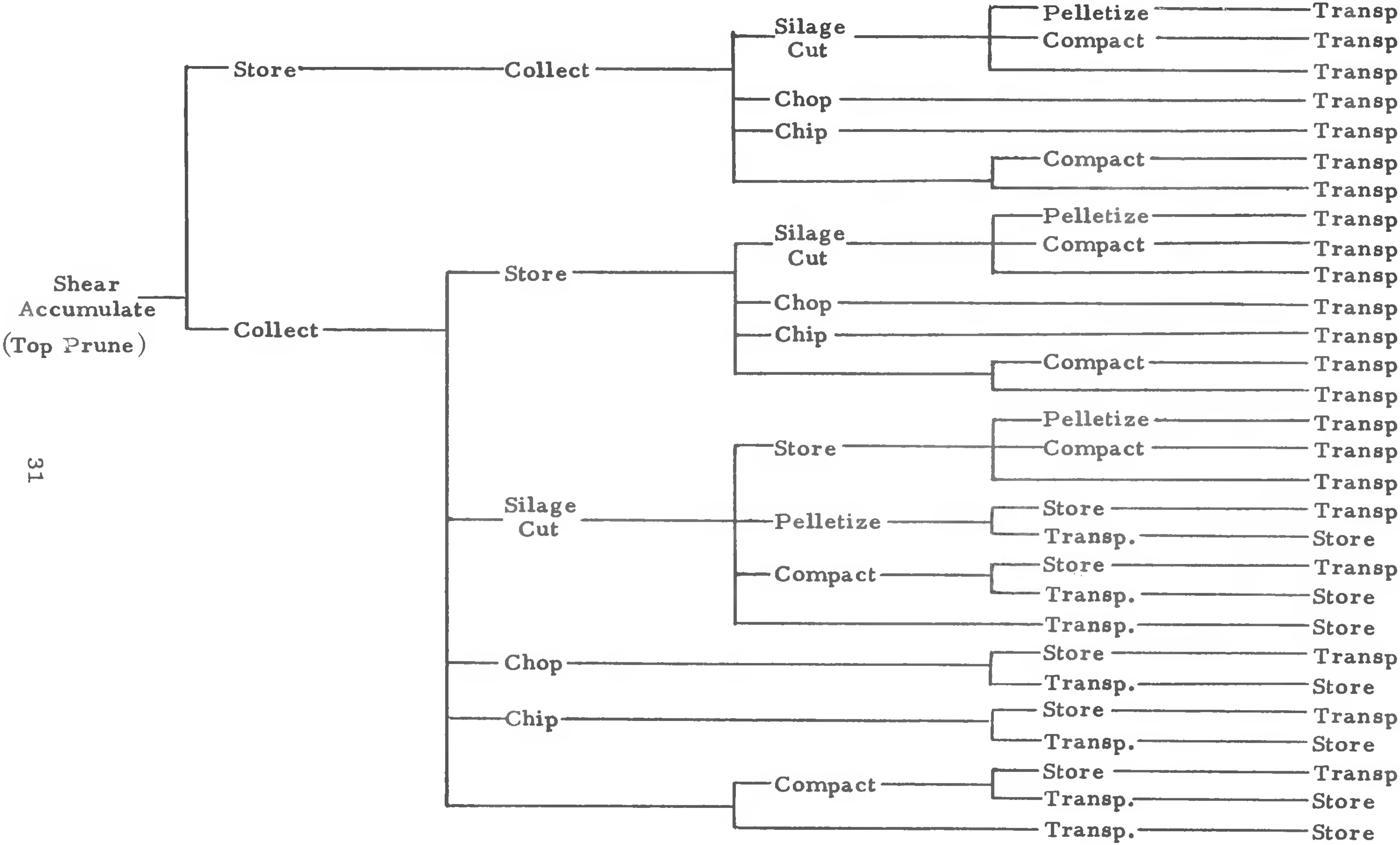


Figure 3. Alternative Harvesting Sequences

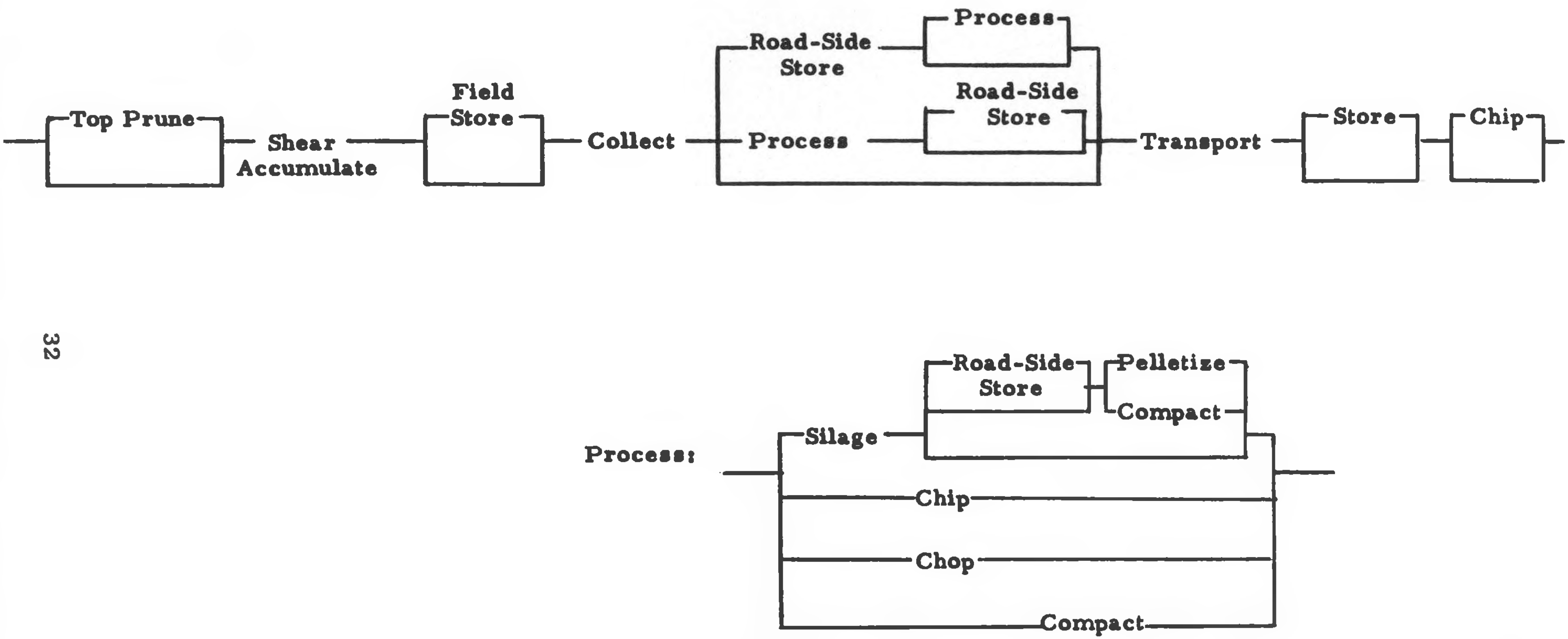


Figure 4. Another Form of the Harvesting Sequences

in Figure 5 for four groups of processing activities defined as:

- Shearing
- Processing (chipping, chopping)
- Transporting
- Plant processing (chipping, if not already chipped)

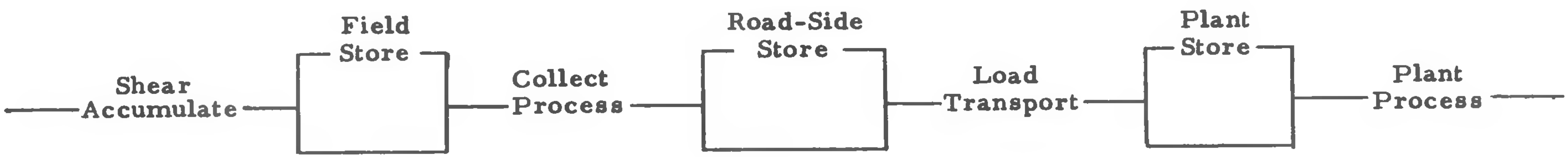
Three types of storage are also defined as:

- Field inventory (after cutting)
- Roadside inventory (after collecting and processing)
- Plant inventory (after transporting)

The model that is developed here is based on this sequence of processes and storage.

The mathematical procedure consists of setting up groups of equations and inequalities (Appendix 2) which analytically represent the relationships among:

- Equipment capacities
  - Shearing rate
  - Processing rate
  - Transporting rate
  - Plant processing rate
- Flow balances
  - Quantity sheared
  - Quantity processed (field)
  - Quantity transported
  - Quantity processed (plant)
  - Demand
- Annual inventory balance
- Constraints on coordinated relationships among equipment, inventories, processing and transporting
- Other constraints (primarily of a mathematical nature)



Alternatives:

- Different types of field equipment
- Option of top pruning

Alternatives:

- Silage/pelletize
- Silage/compact
- Silage
- Chip
- Chop
- Compact
- Collect only

Alternatives:

- Round wood trucks
- Round wood rail cars
- Chip trucks
- Chip rail cars

Alternatives:

- Chipping
- Direct feed only

Figure 5. Schematic Diagram of Material Flow

IV. DATA COLLECTION

Specifications on equipment together with prices were obtained from principal manufacturers of farm machinery, forestry harvesting equipment, sugarcane harvesters, and producers of specialty materials handling equipment such as solid waste and scrap balers. The data was further adjusted as a result of direct communications with manufacturers as well as with agriculture and forest products organizations and associations. The potential application of some types of agriculture machinery to cutting and collecting small diameter hardwoods was also discussed with manufacturers of standard commercial farm machinery.

Appendix 3 is a tabulation of the values obtained which will be used in illustrating the applications of linear programming techniques to an operation involving a 10,000 acre woody biomass farm producing 5 tons per acre per year of wood and supplying at a distance of 10 miles a conversion plant whose annual demand is 40,000 tons. The constants, variables, and indices are as shown in Appendix 2.

The geographical configuration of the farm and plant are shown in Figure 6. Wood is cut, is collected and may be stored in the field. It may also be moved directly from the farm site to a secondary road location where it may be stored or processed followed by storage. Finally the material is moved by truck from the secondary site to the processing plant where it may be stored or first processed and then stored. The characteristics of the transport vehicle needed for traveling within the farm may be such that they make impractical moving the cut material out of the biomass farm on the highway in the same vehicle. Consequently it is doubtful if

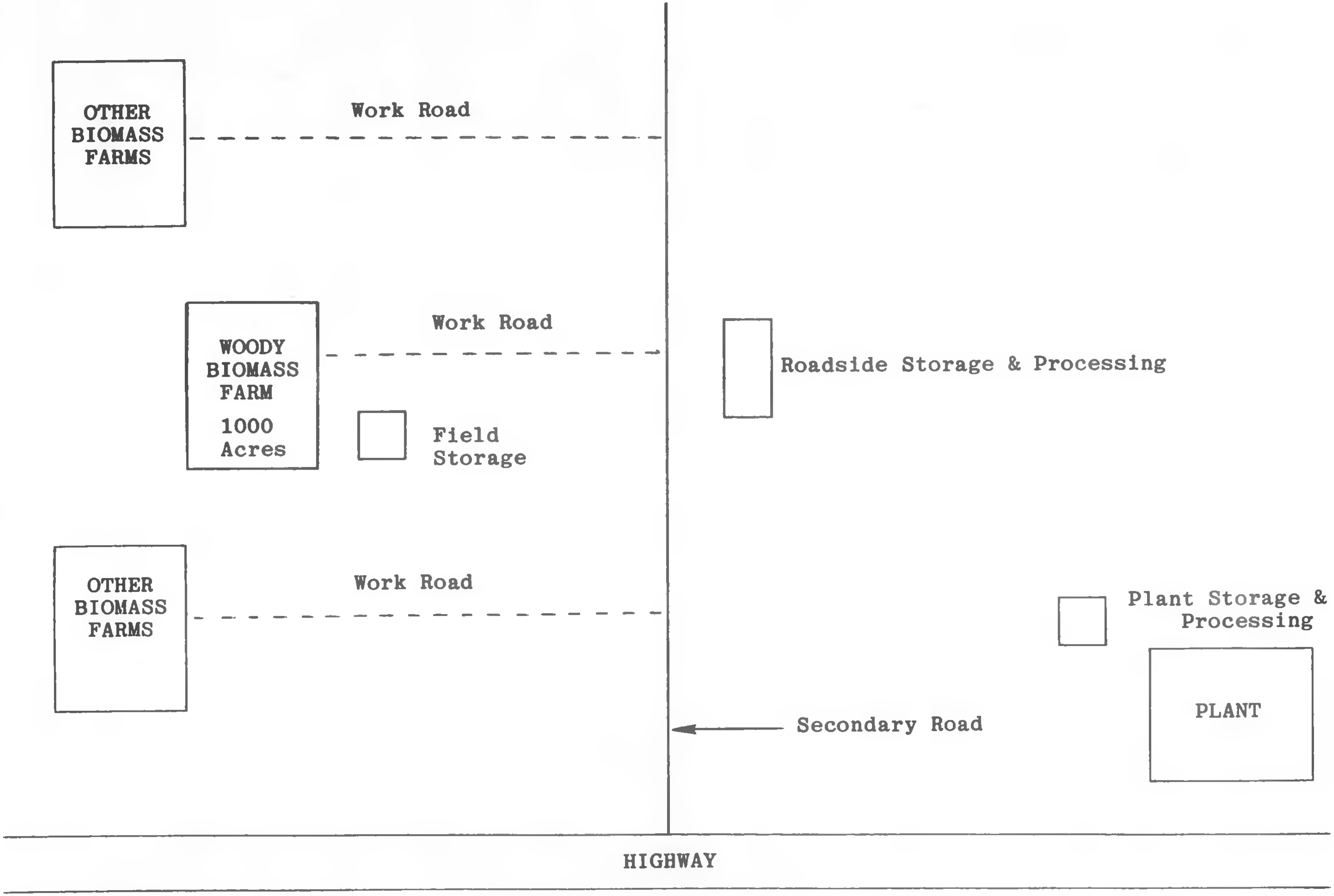


Figure 6. Woody Biomass Farm and Conversion Plant

wood will move directly from the farm to the processing plant in the same vehicle except under very favorable terrain conditions or in the winter season if frozen ground allowed a highway truck to travel unimpeded into the farm area. Processing, such as chipping, is available in two locations. Since transporting of chips is generally controlled by highway weight limitations and not by volume while the reverse may be true for unprocessed biomass, the chipping process at roadside may be economically advantageous. Chipping facilities for wood processing at the plant are also in place since it is beneficial to have open the option of purchasing wood (and also chips) from other suppliers.

It is recognized that prolonged storage of wood or processed wood may produce deterioration. This would result in loss of inventory. At this stage of development of the model, it has not as yet been included so no data are tabulated on deterioration.

Forage harvester data (Figures 3-1, 3-2, 3-3) were obtained from Sperry New Holland on the self propelled models SP1890 and SP1895. The larger unit will produce 75 tons per hour (600 tons per day) of 1/2 inch lengths of 60% moisture corn stalks and ears when standing on reasonably flat soil. It will also handle ears exclusively but will chop these at a much lower rate. Approximately 2 horsepower of capacity is required to feed and chop at a rate of 1 ton per hour of forage. The 250 horsepower maximum output developed by this machine is approximately divided into 170 horsepower for feeding and chopping, 40 horsepower for the forage blower, and 40 horsepower for utilities and to propel the machine.

Currently this machine, including personnel consisting of four operators and associated equipment, contracts out at $85 per hour to harvest a forage crop. The fuel, labor and maintenance costs total approximately $67 per hour ($0.88 per ton) when the machine is operating close to maximum output. For the equipment operating at the speed level of m=3, the top performance of 85 tons per hour (680 tons per day) was assumed to be attainable on flat even ground for a net variable cost per ton of $0.78. An intermediate speed level m=2 was used for harvesting at 80 tons per hour with a variable cost of $0.82 per ton (Figure 3-1).

For terrain conditions (s=2) with uneven and moderately sloping ground (Figure 3-2) the capacity is reduced by only 2% to 590 tons per day for a speed category of m=1. At the higher speed of m=3, the efficiency is reduced to 82% and the capacity is reduced by 3.5% to 655 tons per day. The cost of cutting then becomes $0.97 per ton (Figure 3-2).

For wet conditions of the terrain (s=3), the capacity at all speed ranges is reduced by approximately 10% and efficiencies are about 10% below those for flat, dry ground. Variable costs per ton range from about 12% to 13% above those for flat, dry ground (Figure 3-3).

Additional data were secured from Deere & Company, Inc., on self propelled forage harvesters Model 5440 and 5460 and also from International Harvester on pull-type Model 830. Both are of comparable capacity to that of Sperry New Holland. Also data on the AVCO New Idea Models 708 and 709 self propelled forage harvesters was utilized.

The data on feller bunchers (Figure 3-4, 3-5, 3-6) was compiled using Rome Industries equipment data, job report information and estimates for predicting production rates for various conditions. Owing to the small diameters of the short-rotation woody biomass, feller buncher data for 3 inch trees was used. This is the smallest diameter tree that the standard equipment can effectively handle. For calculation purposes a 3 inch tree is assumed to contain .007 cords of wood and has a green weight of 44 lbs. Accumulator clamp type attachments were assumed since a hypothetical feller for small trees would perform more effectively with this system. Also the tree combine machine harvester data were used since the cutting rate if this equipment is much greater. The Rome Industries data on owning and operating costs for this equipment were incorporated in the calculations of the variable operating costs.

The 70 horsepower Rome Tree Combine will harvest 350 trees per hour of 3 inch diameter weighing 44 lbs. per tree. This is a total of 7.7 tons per hour or 61.6 tons per day (Figure 3-4). This is the production in a 60 minute hour under average field conditions. With a projected 15% improvement in production rate, a level of 72 tons per day could be reached withthis equipment. Currently, the Rome Excavator Accumulator Feller Buncher will operate at 72 tons per day harvesting 75 trees per hour of 4 inch diameter. Each tree weighs approximately 75 lbs.

Figures 3-5 and 3-6 contain estimates of the production that can be expected under poor conditions of slope and soil.

Operating and cost data were obtained

anical sugarcane harvesters used throughout the world. A composite incorporating the characteristics and features of all designs has the capacity, efficiency, and variable operating and maintenance costs shown in Figure 3-7 for ranges of speed m=1, 2, and 3. 50 tons per hour (400 tons per day) was used as representative of capacity although harvesters actually range from 40 tons to 110 tons per hour. In heavy cane they will run at 2 miles per hour and in light cane at 5. The controlling parameter governing speed is maintaining a constant cane throughput in the machine. Above 5 miles per hour, control of the harvester is difficult and visibility poor relative to locating rocks and field stones.

The composite harvesting cost was obtained using data from the Agricultural Research Service of U.S. Department of Agriculture in Belle Glade, Florida. There are about 200 mechanical harvesters in use now. Contract cutting is available from owners of these machines and cutting costs are running about $3.75 per ton including fuel for the equipment. Maintenance costs annually are approximately 25% minimum of the original investment in the equipment. In some cases they have been substantially more owing to heavy usage and wear.

Machines will generally lose about 5 tons of cane per acre which is as much as 10% of the crop. On the favorable side, the best efficiency that could be expected would be a 5% loss.

(Handcutting using Jamaican labor loses about 2 to 3 tons per acre.)

Figures 3-8 and 3-9 show projected data for wet and muddy conditions. For the most part, cane is grown only on flat areas other than in Hawaii.

Data indicate that all sugarcane harvesters are overpowered by conventional standards of farm crop harvesting. The largest is the 400 horsepower Stubenberg self propelled machine used in Hawaii in fields producing 100 tons per acre. These machines are designed as long cane cutters or short cane chopper harvesters. They are massive machines weighing about 37 tons and cost approximately $450,000 to $500,000. The specifications, in brief, for these machines are:

Harvesting capacity	50 - 80 tons/hr.
Engine	400 hp diesel
Speed	0 - 3.5 mph
Track	9 feet
Ground clearance	16 inches
Ground pressure	6 psi
Turning circle	12 feet
Cane billet length	22 inches
Cane topping or pruning	(not used)
Maximum slope of terrain	25%

Generally all sugarcane harvesters are overdesigned owing to the very rugged fields and conditions in which cane is grown. Furthermore, over a period of time when ratooning (coppicing) takes place, multiple stalks-as many as 10 to 15-grow out of the base and must be severed by the cutter. On the average as many as 4 or 5 stalks are cut when a single plant is harvested at ground level.

The small turning circle is characteristic of these harvesters since growers in order to utilize all land typically leave only 21 or 22 feet of space at the end of a row for turning the machine.

A characteristic of the harvesting system revealed by data is that the 1-row machine appears to be superior to a 2-row machine since it is easier to use and control.

The harvesters considerd in compiling the composite machine characteristics are:

Type	Manufacturer
Models 102, 105, 201, 205	Massey Ferguson Ltd.
Models S-6000 and S-15	J & L Engineering Company (Honolulu Iron Company)
Mark II Robot 364 and Model 464	Toft Bros. Industries Ltd.
Claas Libertadora 1400	Claas Maschinenfabrik Gmbh.
2-Row Cutter-Windrower plus Loader-Cleaner machines	Sugar Cane Growers Cooperative of Florida
Long Cane Harvester, Short Cane Harvester	Stubenberg Company Ltd.
Model M-SCH-1	U.S. Sugar Corporation (M-R-S Manufacturing Co.)
2-Row Cane Combine	Thomson International Company
Cameco Model CH-1000	Cane Machinery & Engineering Company Inc.

Wood chipper data were obtained primarily from Morbark Industries as this organization has over 500 units of a mobile Model 22 operating in the field. In addition, data was secured from several other manufacturers.

Production capacity and cost of operating information obtained from Morbark (Figure 3-10) plus current fuel and labor increases show that at a level of 275 tons per day for 200 days per year for a 5 year period, the Model 22 Chip-arvestor has the following costs:

Maintenance	$0.95 per ton	
Fuel	.90	250 gal/day diesel fuel at $1.00 per gal.
Labor	1.72	6 men @ $10.00/hr.
Total Variable Cost	$3.57 per ton of chips	

The capacity, efficiencies, and costs for m=2 and 3 were projected based on data from the manufacturer that this model is fully capable of reaching a rate of 400 tons per day on a sustained basis (Figure 3-11, 3-12).

Development data on chip balers was provided by waste and bark baling manufacturers and forest products industries involved in this activity. It is estimated that a maximum rate (m=3) of production of 24 bales per hour (30 tons per hour of input chips) can be reached and sustained 2 shifts per day, 6 days per week throughout the year. The variable costs involved at a level of output of 8 hours per day (240 tons/day) are (Figure 3-13):

Maintenance	$0.20 per input ton	
Fuel (Power)	.30	
Labor	1.20	3 men per shift @ $12 per hr.
Baling Wire	1.05	
Total Variable Cost	$2.75 per input ton	

The bale requires 9 wraps of a high tensile strength wire. This requirement totals 4.4 lbs. of wire per bale at approximately $0.30 per pound. The baling process requires high compression pressures to reduce a 2500 lb., 50% moisture bale down to a 2000 lb. bale with 27.5% moisture. The high cost 12 gauge wire is a necessity to maintain the bale's integrity. The bulk density has been increased from 25 to 40 lbs. per cubic foot by compression pressures of over 900 lbs. per square inch.

At a reduced rate of operation (m=1), the baler can make 20 bales per hour and this rate can be maintained by the 3 man operating crew for a total of 200 tons per 8 hour day (Figure 13). A rate of 22 bales per hour has been estimated for an intermediate rate which results in a production rate of 220 tons per day. For unfavorable conditions of terrain and weather a 4% reduction in production rate has been assumed and for poor conditions (wet and muddy) it is assumed that an additional 4% reduction in baling production would occur.(Figures 3-14, 3-15).

Agricultural cubing system data was obtained from Deere & Company. The cubing operation is virtually a small baling system whose purpose is to reduce the truck and storage space for crops that would ordinarily be baled. Cubes require about 50% of the space that are required by crop bales. The density runs between 45 and 55 pounds per cubic foot while the bulk density is 25 to 32 pounds per cubic foot. Trucks can be loaded to their weight limit without exceeding height and width restrictions.

The cubing process requires low moisture-below 12%-in order to maintain durability of the cube. Higher moisture can be tolerated but may sacrifice life of the product. The natually soluble adhesives found in a number of crops is needed to form a satisfactory product.

A John Deere Model 425 Cuber has a production capacity of 5 to 9 tons per hour and will travel in a range of 2 to 4 miles per hour through the field. Estimates have been made as to the production that would be experienced with this equipment under poor conditions of sloping terrain and soil wetness. (Figures 3-16, 3-17, 3-18).

The variable operating costs have been estimated based on a single operator for the equipment plus the 216 horsepower requirements to produce 5 tons per hour and propell the vehicle. These values are contained in Figures 3-16, 3-17, and 3-18.

U. S. Department of Agriculture data on transporting sugarcane to the mill from field totals approximately $1.50 per ton in 1980. This is up from a 1978 value of $0.60 per ton. In truck vehicle operations of this type the fixed costs are approximately 38% of the total costs. The remaining variable costs are wages of the operator, 38%, maintenance, 13%, and fuel, 11%.

Assuming that this cost partition of 38% fixed and 62% variable can be extended to 20 ton sugarcane truck-trailers, the variable cost of transporting the cane to the mill equals $0.37 per ton. A round trip distance of 10 miles has been assumed for the average cane field to mill distance since for the most part the mill is as close to the field as can be obtained. For a 20 mile round trip distance from a plant to field, the costs would be $0.74 per ton (Figure 3-19). For values of m=2 and m=3, little change in unit cost is seen. However for unfavorable weather conditions as in s=2 and s=3, transporting falls off substantially as trucks and wagons frequently become stuck in these poor conditions. Further, additional field traffic by harvesters and transports causes excessive flotation problems in wet conditions. These data are contained in Figures 3-20 and 3-21.

Wood conversion data, primarily gasification, was extracted from the literature on proposed gasification plants and processes (Appendix 1). For plants under development that propose to process coal or wood, approximately one-third of the total gasification costs will consist of the cost of the feedstock; one-third consists of operating costs; and about one-third is tied up in meeting the cost of the capital needed for the undertaking. Figure 3-22 contains data that has been scaled down to a 127 ton per day plant from plant designs that are in the range of 1,500 to 10,000 tons per day. Figures 3-23 and 3-24 carry the same production rates as it is not as yet known what change rate may develop between using a 1 inch chip and a 3 inch chip. The cost in the latter two figures reflect the expected increased cost in handling and processing the larger chips.

Transport unit production and cost data are generally uniform (Figures 3-25, 3-26, and 3-27). For a 20 ton chip carrying vehicle operating 8 hours per day and traveling 200 miles per day for an annual total of 50,000 miles, variable operating costs have been obtained as follows:

Fuel calculated at $1.00 per gallon and 6 miles per gallon for the vehicle = $8,330

Labor at $10.00 per hour for a 250 day year
= $20,000

Maintenance calculated at $0.22 per mile for used trucks
= $11,000

Total = $39,330 per year

This represents a cost of $0.79 per mile or $0.04 per ton mile.

For a 20 mile round trip between field and mill, the variable transport cost per ton is thus $0.80.

The operating and cost data for wet and wet, muddy conditions are substantially different from the flat (s=1) condition since the field trucks and trailers have great difficulty in moving in poor weather and under poor soil conditions.

V. RESULTS

The results of this study can be summarized in two principal categories. They are:

Data - There have been extensive developments by the agricultural and forest products industries in the practice of harvesting their crops which is directly applicable to close-spaced, short-rotation woody biomass farms. These developments are not simply confined to the cutting of grain crops or trees but have been directed at the problems surrounding the improving of the transporting and processing of the crop in the field. The sugarcane industry similarly has focussed on improving the harvesting of cane and developing ways that will improve the transporting and processing in the in the field. Much of the existing equipment is capable of being used directly in harvesting short-rotation woody biomass; however this application is expected to result in decreased life and increased maintenance. The heavy duty sugarcane harvesters appear to be capable of being modified to be used immediately to harvest small diameter trees and chop them into billets for further processing. The problem as to how the resulting residues consisting of foliage and twigs should be used is as yet unresolved.

Modeling - The efforts directed at modelling the shearing, transporting, and storing the biomass were successfull and indicate that there is no foreseeable difficulties. Further refinement of the model can be made as the system develops in sophistication. Insufficient funds were available to obtain solutions on the computer at this time. Consequently, no precise results can be given as to the optimized solution for the problem structured in this report.

VI. CONCLUSIONS AND RECOMMENDATIONS

The operations of agricultural, forestry, and sugarcane harvesting are closely allied both in dimension and technique to that required for short-rotation, close-spaced woody biomass plantations. It will be valuable to use as much of the existing technology as can be effectively adopted. One of the major problems that appears likely to develop is that which surrounds the using of the harvesting equipment under non-ideal conditions of weather and configuration of terrain. Cost of the biomass will be important and non-ideal environmental conditions plus poor terrain is seen to contribute to rapid falloff in production rates and efficiencies.

Since cost optimizing the harvesting system is vital to the success of the program, it is recommended that modelling continue and computer solutions obtained for various configurations of the system.

Experimental programs should be started involving cutting actual stands with existing machines in order to determine what problems lie ahead in utilizing such technology and machines as those employed in sugarcane harvesting.

APPENDIX 1 - WOOD CONVERSION SYSTEMS

Virtually no commercial plants have been designed, engineered and built using wood as a feedstock other than those for producing charcoal or for direct burning of wood chips. Consequently any study directed at producing fuels or chemicals from wood needs to be based on technology developed for one or more other resources. The Union Carbide Corporation Purox systems and the Moore-Canada Gasifier are the only two gasifiers closely linked to using wood, although the former was designed for the purpose of employing municipal solid waste as the feedstock. Since many systems designed for converting coal to various fuels and chemicals incorporate characteristics and features that would be needed in a wood-using facility, information developed for these systems will be utilized in developing and evaluating the characteristics and properties of the wood feedstock that will be required. Wood particle or chip size and moisture content are among the major variables to be considered.

Among the various systems being developed by various organizations to use wood and wood waste as feedstock are the following:

Moore-Canada gasifier developed in British Columbia, will produce (using air) low Btu gas (180 Btu/Scf) from hogged wood waste. A pilot plant capable of hauling 18 tons per day of wood is in operation using a 5.5 foot diameter gasifier. Also a commercial facility is in operation using two 9.5 foot diameter gasifiers each capable of handling 60 tons per day of wood waste.

Battelle has made pilot plant studies on the partial oxidation (using air and steam) of municipal solid waste in the State of Washington. The tests conducted in a 3 foot diameter gasifier included using wood chips as feedstock.

Union Carbide Corporation has developed over a period of ten years a system (Purox) for the partial oxidation of municipal solid waste using oxygen. This system is capable of accepting wood waste to produce a gas composed mainly of CO, H_2, and CO_2. The original 5 ton per day system has been scaled up to 200 tons per day.

Alberta Industrial Development Ltd. in Edmonton, Canada, has developed and is using Thermex Process in a 50 oven-dried ton per day plant to produce low Btu gas. This fluidized-bed type gasifier requires 2 inch particle size wood waste.

Copeland Company has constructed for the pulp and paper industry several fluidized-bed reactors to dispose of matter in waste liquor. This equipment is capable of using wood and wood waste as feedstock.

For the most part the well-known coal gasifiers, namely Lurgi, Winkler, and Koppers-Totzek are not particularly well suited to handle wood feedstock because of requirements on uniform or small particle size for the feedstock.

The moisture in wood waste or recently cut wood approaches in weight that of the dry wood content. In partially oxidizing wood in a gasifier, a crude gas is obtained containing large quantities of water vapor, carbon dioxide, nitrogen and various organics, tars, and hydrocarbons. This gas (principally methane, hydrogen and carbon monoxide) must be cleaned before further chemical use of the gas can take place.

The end use of the crude gaseous or liquid products derived from the wood will dictate much of the chemical processing. For example, with increasing amounts of impurities in the processed stream, the synthesis of a product such as methanol fuel will require higher pressure and hence higher costs to minimize the effects of these inert impurities.

The economics of raw material processing are strongly dependent upon facility capacity. Because investment in chemical plants generally increases as the 0.6 power of capacity increase, unit cost reduction is commonly obtained in that industry by building high capacity facilities. Consequently a large processing facility with large raw materials handling capabilities would result in favorable costs.

Estimates have been made of the capital investment required for moderate size chemical plants that convert wood and wood waste to such chemical fuels as methanol. For a plant that will process 1500 tons of wood or cellulose waste per day (15 billion Btu/day) and produce about 400 tons/day of methanol, a plant investment of $64 million (1975 dollars) is required. Studies show that of this total approximately 5% or $3,000,000 is invested in the wood yard. A National Academy of Science study in 1976 reports that a 900 ton/day (9 billion Btu/day) wood waste chemical processing plant capable of producing 300 ton/day of methanol would involve an investment of $29.5 million.

A similar type plant based on the Union Carbide Purox process and designed to gasify municipal solid waste at an input rate of

1500 tons/day was estimated by engineers to cost $56 million in 1974. In this system a marshalling area and classification yard replaced the wood yard.

On a larger scale, investigation directed at plant investments for conversion facilities using as feedstock coal in place of wood obtained the following (1975 dollars):

	Input Capacity (10")	Cost (10^6)
AEC	2.1 Btu	$253
ORNL	3.7 Btu	$279-$364
AEC	2.37 Btu	$241
NAS	2.33 Btu	$240 (1976)

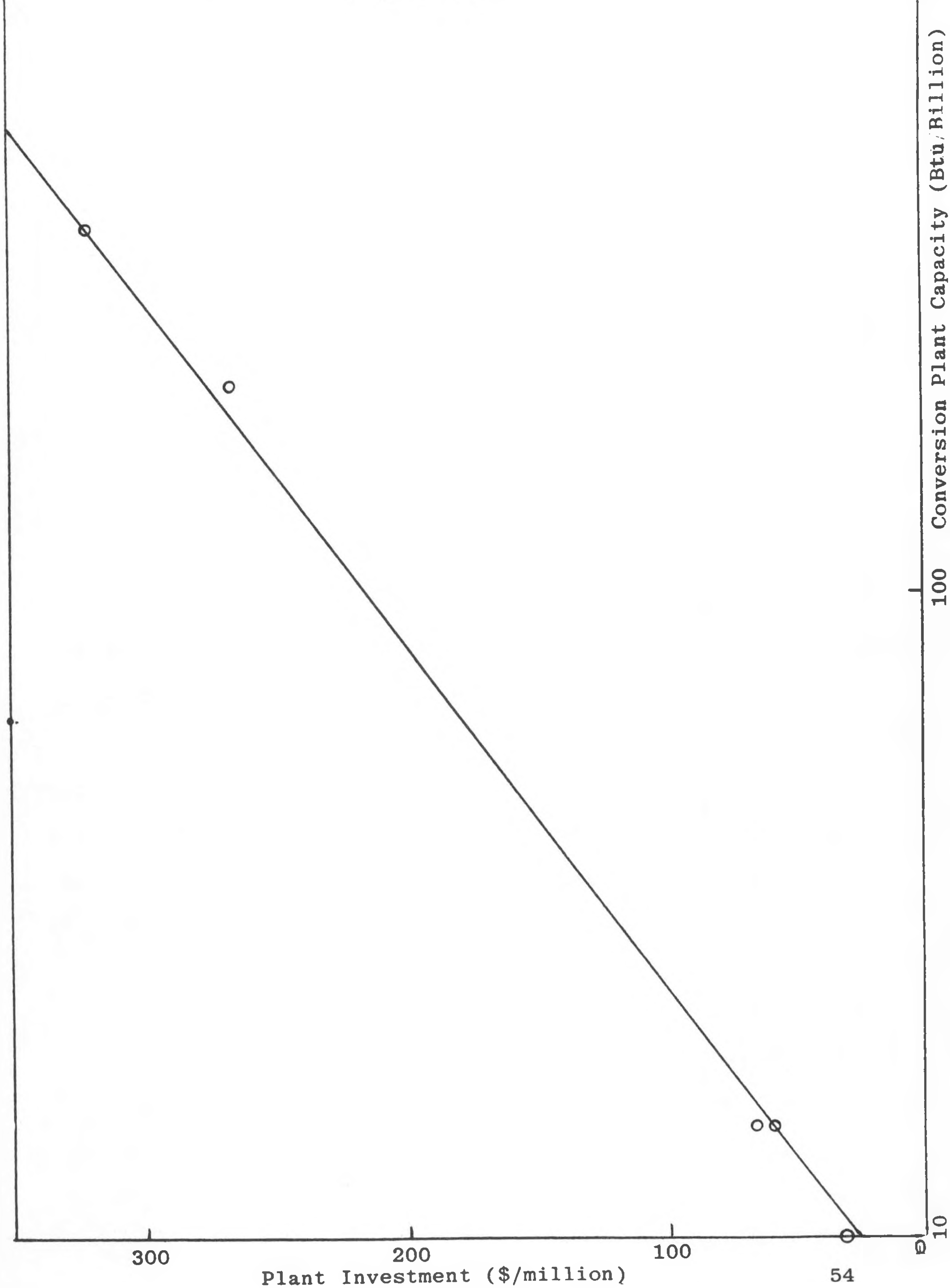
Figure 1-1 is a plot showing plant investment as a function of plant capacity for various sizes and systems recently studied.

Estimates of raw material costs vary considerably depending upon the form of the wood feedstock.

At one extreme is hogged wood waste containing as much as 50% moisture by weight. At the other extreme is feedstock consisting of well-dried (oven-dried) pulverized wood or chips. Estimates have been made (1976) by the Forest Service of the cost of collecting and transporting wood waste to a central processing site. They would range between $15 and $34 per oven-dried ton. More recently (1978) investigators have concluded that at a cost between $10 and $30, half of the estimated total wood waste tonnage in the country of 20 to 30 billion tons would be available.

Since wood waste has value both as a source of chemicals and fuel, its minimum market place value is generally its lower value as a fuel when compared to other conveniently available fuels. From this standpoint, wood with a cost of $24.00 per ton and heat content of 8000 Btu/lb. would be equivalent to coal at $36.00 per

Figure 1-1



1000
Conversion Plant Capacity (Btu/Billion)
100
10
0
300
200
100
54
Plant Investment ($/million)

ton and heat content of 12000 Btu/lb. assuming equal efficiency of combustion. Consequently this value would determine the lowest cost for wood waste to be used in chemical processes or for conversion to other fuels. The use of wood waste for construction such as in particle board or to replace pulpwood would be a higher value application and therefore its utilization in those applications would also be set by its fuel value. By way of comparison the delivered price for pulpwood ranges between $30 and $60 per oven-dried ton.

Operating costs (excluding raw materials) in a wood conversion plant are estimated to be comparable or slightly less than those for coal conversion plants since more processing facilities are required for coal owing to greater ash content plus sulfur. Both coal and wood are viewed as commercially supplied material. However, coal preparation facilities and wood preparation facilities are included in the plant investment.

Studies made in 1974 by the AEC and others showed that for coal conversion plant design in the range of 9900 tons/day to 14900 tons/day (input), operating costs (exclusive of coal) would be in the range of $0.53 to $0.72 per million Btu output of the plant. Capital costs (15% annually of capital investment) were calculated to be $0.51 to $1.12 per million Btu output for these same size plants. Coal costs per million Btu output were estimated to range from $0.47 to $0.73. In summary, each of the three major categories of the total cost was about one-third of the total. Consequently the total cost of a product involving the gasifying of a carboneous material such as coal or wood appears to be quite sensitive to the raw material cost. A $3 per ton change in the wood (or coal) delivered cost will make about a $1 per ton change in the cost of the processing plant's output.

APPENDIX 2 - LINEAR PROGRAMMING MODEL

The equations used in the linear programming system to represent the relationships between equipment capacities, material flow, and inventories in the harvesting system are described in the following paragraphs. A tabulation of the symbols and nomenclature used for variable, constants, and indices is included.

The objective function represents the total cost involved in supplying the processing plant's demand over the one year period within the constraints imposed. This function is composed of annualized investment costs, operating and maintenance costs, and inventory costs together with performance data compiled from information supplied by manufacturers of agricultural, forestry, and sugarcane harvesting equipment and machinery.

By linear programming optimization techniques the minimum value of the objective function is obtained.

Equations

Equipment Capacities

The shearing rate with each type of equipment during a period cannot exceed the available capacity. The capacity depends on the mode of operation and the conditions in the region.

$$\sum_m \sum_r \frac{1}{CS_{ims_r}} XS_{imrt} \leq NS_i \qquad \forall i,t$$

The processing rate with each type of equipment during a period cannot exceed the available capacity. The capacity depends on the mode of operation, the conditions in the region, and the product being made.

$$\sum_m \sum_p \sum_r \frac{1}{CR_{imps_r}} XR_{imprt} \leq NR_i \qquad \forall i,t$$

The transporting rate with each type of equipment during a period cannot exceed the available capacity. The capacity depends on the mode of operation, the distance and conditions of the region, and the product being transported.

$$\sum_m \sum_p \sum_r \frac{1}{CT_{imps_r d_r}} XT_{imprt} \leq NT_i \qquad \forall i,t$$

The plant processing rate with each type of equipment during a period cannot exceed the available capacity. The capacity depends on the mode of operation and the product being converted.

$$\sum_m \sum_p \frac{1}{CP_{imp}} XP_{impt} \leq NP_i \qquad \forall i,t$$

Flow Balances

The amount sheared cannot exceed the amount available annually in a region times the cutting efficiency. The efficiency depends on the equipment, and its mode of operation. Daily rates are converted to tons per period.

$$\sum_i \sum_m \sum_t \frac{D_t}{ES_{im}} XS_{imrt} \leq A_r \qquad \forall r$$

The amount processed equals the amount cut plus the net amount withdrawn from field inventories during a period. This is multiplied by an efficiency which depends on the equipment, its mode of operation, and the product being made.

$$\sum_i \sum_m \sum_p \frac{D_t}{ER_{imp}} XR_{imprt} = WF_{rt} - WF_{r,t+1} + \sum_i \sum_m D_t XS_{imrt} \qquad \forall r,t$$

The amount of a product transported equals the amount processed plus the net amount withdrawn from roadside inventories in a period. This is multiplied by an efficiency (generally close to 1.0) which depends on the equipment, its node of operation, and the product being transported. Note that XT is the amount delivered (rather than the amount leaving the woods).

$$\sum_i \sum_m \frac{D_t}{ET_{imp}} XT_{imprt} = WR_{prt} - WR_{pr,t+1} + \sum_i \sum_m D_t XR_{imprt} \qquad \forall p,r,t$$

The amount of a product processed at a plant equals the amount delivered plus the net amount withdrawn from plant inventories in a period. This is multiplied by an efficiency which depends on the equipment, its mode of operation, and the product being processed.

$$\sum_i \sum_m \frac{D_t}{EP_{imp}} XP_{impt} =$$

$$WP_{pt} - WP_{p,t+1} + \sum_i \sum_m \sum_r D_t XT_{imprt} \qquad \forall p,t$$

The amount processed must equal the required demand during a period. Note that XP is the tons of material after processing product p to the form required in the plant.

$$\sum_i \sum_m \sum_p D_t XP_{impt} = R_t \qquad \forall t$$

Annual Inventory Balance

The harvesting is assumed to follow an annual cycle. Thus, the inventory at the start of a new year is the same as the amount at the close of a year. This is reflected in the model by defining the following equivalences where T is the number of periods in a year.

$$WF_{r,T+1} \equiv WF_{r,1}$$

$$WR_{pr,T+1} \equiv WR_{pr,1}$$

$$WP_{p,T+1} \equiv WP_{p,1}$$

Equipment Relationships

A variety of particular relationships may hold. For example, one unit may be an integrated shearer and chipper. In this case, selection of the NS and NR variables must be coordinated. Suppose this unit is denoted by i in the shearer alternatives list and by j in the processing list. Then we have:

$$NS_i = NR_j \qquad \text{for this } (i,j)$$

Also, no field inventory before chipping can occur. The amount sheared in a mode must be the same as the amount chipped in that mode. Thus, we require

$$\sum_r XS_{imrt} = \sum_p \sum_r XR_{jmprt} \qquad \forall m,t \quad \text{for this } (i,j)$$

Note that the efficiency constant ER is unity in this case.

This illustrates how specifics pertaining to a given situation can be modeled. Other types of coordination of equipment, processing, etc., may be similarly included.

Other Constraints

All variables are non-negative and the N variables must take on integer values. The variables may be bounded as appropriate.

Inventory losses are not modeled explicitly. Primarily these are moisture losses which depend non-linearly on time in storage and handling losses associated with loading and unloading. The moisture loss is often desirable since this reduces transportation weight and may help the plant operation. Modeling these losses needs to take explicit account of the relationship of weight, moisture, and Btu content. Subject to linearity restrictions, these relations can be included although the resulting equations are more complex to describe. It can also increase the dimensionability so the value, especially in the time frames considered, must be considered.

Objective Function

Costs may be associated with each of the variables in the model. Costs are based on an annual period. The following are the most important costs:

Investment Costs

CNS_i - The annualized investment cost and those maintenance costs incurred annually for a shearing unit of type i ($).

CNR_i - The annualized investment cost and those maintenance costs incurred annually for a processing unit of type i ($).

CNT_i - The annualized investment cost and those maintenance costs incurred annually for a transportation unit of type i ($).

CNP_i - The annualized investment cost and those maintenance costs incurred annually for a plant processing unit of type i ($).

Processing Costs

CXS_{ims} - The operating cost and those maintenance costs proportional to operations for shearing units of type i used in mode m and condition s ($/ton).

CXR_{imps} - The operating cost and those maintenance costs proportional to operations for processing units of type i used in mode m to produce product p under condition s ($/ton)

CXT_{impsd} - The operating cost and those maintenance costs proportional to operations for transportation units of type i used in mode m for transporting product p under condition s over distance range d ($/ton).

CXP_{imp} - The operating cost and those maintenance costs proportional to operations for plant processing units of type i used in mode m for converting product p ($/ton).

Inventory Costs

The only inventory costs likely to be significant are for the land and/or buildings used at the plant. If this is the case, the following variables, costs, and equations are required.

Variables:

ZP_p - the plant inventory capacity for product p (tons)

Costs:

CZP_p - the annualized investment cost per unit of plant inventory capacity ($/ton).

Equations:

$$WP_{pt} \leq ZP_p \qquad \forall t$$

The objective function is the sum of these terms:

$$\begin{aligned}
\text{Min} & \sum_i CNS_i \; NS_i \\
& + \sum_i CNR_i \; NR_i \\
& + \sum_i CNT_i \; NT_i \\
& + \sum_i CNP_i \; NP_i \\
& + \sum_i \sum_m \sum_r \sum_t CXS_{ims_r} \; XS_{imrt} \\
& + \sum_i \sum_m \sum_p \sum_r \sum_t CXR_{imps_r} \; XR_{imprt} \\
& + \sum_i \sum_m \sum_p \sum_r \sum_t CXT_{imps_r d_r} \; XT_{imprt} \\
& + \sum_i \sum_m \sum_p \sum_t CXP_{imp} \; XP_{impt} \\
& + \sum_p CZP_p \; ZP_p
\end{aligned}$$

Variables

Available Equipment

NS_i - Number of shearing units of type i (integer)

NR_i - Number of processing units of type i (integer)

NT_i - Number of transportation units of type i (integer)

NP_i - Number of plant processing units of type i (integer)

Processing Rates

XS_{imrt} - Daily shearing rate using type i units in mode m in region r during period t (tons/day).

XR_{imprt} - Daily processing rate using type i units in mode m to make product p in region r during period t (tons/day).

XT_{imprt} - Daily transporting rate using type i units in mode m to carry product p from region r to the plant during period t (tons/day).

XP_{impt} - Daily processing rate using type i units in mode m using product p during period t (tons/day).

Inventory Levels

WF_{rt} - Inventory of raw material in the field in region r at the start of period t (tons).

WR_{prt} - Inventory of product p at the roadside in region r at the start of period t (tons).

WP_{pt} - Inventory of product p at the plant at the start of period t (tons).

Constants

CS_{ims} - Daily capacity of shearing units of type i used in mode m under condition s (tons/day)

CR_{imps} - Daily capacity of processing units of type i used in mode m to produce product p under condition s (tons/day)

CT_{impsd} - Daily capacity of transportation units of type i used in mode m to carry product p under condition s over distance range d (tons/day)

CP_{imp} - Daily capacity of plant processing units of type i used in mode m to convert product p (tons/day)

ES_{im} - Efficiency in cutting available timber (= 1 - loss rate) using equipment of type i in mode m

ER_{imp} - Efficiency in processing cut trees using equipment of type i in mode m to produce product p

ET_{imp} - Efficiency in transporting product p with equipment of type i in mode m. This reflects loading losses and losses in transit.

EP_{imp} - Efficiency in processing product p at the plant with equipment of type i in mode m

D_t - Number of days of operation in period t

A_r - Available timber during the year in region r (tons)

R_t - Required demand at the plant in period t (tons)

Indices

i - types of equipment (see alternatives in Figure 3)

m - mode of operation of equipment (e.g. different speeds)

p - types of products (e.g. small chips, roundwood)

r - region around the plant (permits consideration of distance and condition)

t - time period (e.g. month in annual cycle horizon)

s - condition of forest (e.g. marshy, hilly, rocky)

d - distance range of region (e.g. within 5 miles, within 20 miles)

APPENDIX 3 - PROGRAM DATA

The 27 figures in this appendix contain the values of the data to be used for the parameters, coefficients, and constants employed in the linear programming model described in Appendix 2.

Shearing Unit (i = 1) Forage Harvester

Condition: Flat (s = 1)

	m = 1	m = 2	m = 3	
CS	600	640	680	Ton/Day
ES	91	87	85	%
CXS	.88	.82	.78	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-1

Shearing Unit (i = 1) Forage Harvester

Condition: Uneven Terrain (s = 2)
Sloping

	m = 1	2	3	
CS	590	620	655	Ton/Day
ES	90	89	82	%
CXS	.94	.94	.97	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-2

Shearing Unit (i = 1) Forage Harvester

Condition: Wet (s = 3)

	m = 1	2	3	
CS	545	580	620	**Ton/Day**
ES	80	80	80	**%**
CXS	1.13	1.10	1.05	**$/Ton**

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-3

Shearing Unit (i = 2) Feller Buncher

Condition: Flat (s = 1)

	m = 1	m = 2	m = 3	
CS	61.6	64.8	72.0	Ton/Day
ES	90	89	88	%
CXS	6.61	7.12	7.16	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-4

Shearing Unit (i = 2) Feller Buncher

Condition: Sloping (s = 2)
Poor Terrain

	m			
	1	2	3	
CS	46.0	48.0	50.0	**Ton/Day**
ES	82	81	80	**%**
CXS	10.00	11.00	11.00	**$/Ton**

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-5

Shearing Unit (i = 2) Feller Buncher

Condition: Wet (s = 3)

	m = 1	m = 2	m = 3	
CS	32.0	32.4	36.0	Ton/Day
ES	85	85	87	%
CXS	13.00	14.00	14.00	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-6

Shearing Unit (i = 3) Sugarcane Harvester

Condition: Flat (s = 1)

	m = 1	m = 2	m = 3	
CS	400	400	400	Ton/Day
ES	91	89	87	%
CXS	3.75	3.80	3.85	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-7

Shearing Unit (i = 3) Sugarcane Harvester

Condition: Wet (s = 2)

	m: 1	2	3	
CS	400	400	400	Ton/Day
ES	89	87	85	%
CXS	4.50	4.54	4.60	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-8

Shearing Unit (i = 3)   Sugarcane Harvester

Condition: Wet (s = 3)
             Muddy

	m = 1	m = 2	m = 3	
CS	380	380	380	Ton/Day
ES	84	84	84	%
CXS	4.67	4.74	4.80	$/Ton

Capacity of Cutting, CS_{ims}

Efficiency of Cutting, ES_{ims}

Cost of Cutting, CXS_{ims}

Figure 3-9

Processing Unit (i = 1) Chipper

Product: Wood Chips - 1 inch (p = 1)

Condition: Flat (s = 1)

	m = 1	m = 2	m = 3	
CR	275	315 ·	350	**Ton/Day**
ER	90	89	87	**%**
CXR	3.57	3,64	3.64	**$/Ton**

Capacity of Chipping, CR_{imps}

Efficiency of Chipping, ER_{imp}

Cost of Chipping, CXR_{imps}

Figure 3-10

Processing Unit (i = 1) Chipper

Product: Wood Chips - 1 inch (p = 1)

Condition: Sloping (s = 2)
Poor Terrain

	m = 1	m = 2	m = 3	
CR	260	300	330	Ton/Day
ER	89	88	86	%
CXR	3.75	3.80	3.85	$/Ton

Capacity of Chipping, CR_{imps}

Efficiency of Chipping, ER_{imp}

Cost of Chipping, CXR_{imps}

Figure 3-11

Processing Unit (i = 1) Chipper

Product: Wood Chips - 1 inch (p = 1)

Condition: Wet (s = 3)
Muddy

	m = 1	2	3	
CR	235	270	300	Ton/Day
ER	82	81	80	%
CXR	4.35	4.40	4.45	$/Ton

Capacity of Chipping, CR_{imps}

Efficiency of Chipping, ER_{imp}

Cost of Chipping, CXR_{imps}

Figure 3-12

Processing Unit (i = 2) Baler

Product: Wood Chips - 1 inch (p = 1)

Condition: Flat (s = 1)
Terrain

	m = 1	m = 2	m = 3	
CR	200	220	240	Ton/Day
ER	90	90	90	%
CXR	2.77	2.76	2.75	$/Ton

Capacity of Compacting, CR_{imps}

Efficiency of Compacting, ER_{imp}

Cost of Compacting, CXR_{imps}

Figure 3-13

Processing Unit (i = 2) Baler

Product: Wood Chips - 1 inch (p = 1)

Condition: Wet (s = 2)

	m = 1	m = 2	m = 3	
CR	192	212	232	Ton/Day
ER	90	90	90	%
CXR	2.87	2.85	2.83	$/Ton

Capacity of Compacting, CR_{imps}

Efficiency of Compacting, ER_{imp}

Cost of Compacting, CXR_{imps}

Figure 3-14

Processing Unit (i = 2) Baler

Product: Wood Chips - 1 inch (p = 1)

Condition: Wet (s = 3)
Muddy

	m = 1	m = 2	m = 3	
CR	184	204	224	Ton/Day
ER	88	88	88	%
CXR	3.00	2.97	2.93	$/Ton

Capacity of Compacting, CR_{imps}

Efficiency of Compacting, ER_{imp}

Cost of Compacting, CXR_{imps}

Figure 3-15

Processing Unit (i = 3) Cuber

Product: Biomass Block - 2.5 cu.in. cube (p = 2)

Condition: Flat, Dry (s = 1)

	m = 1	m = 2	m = 3	
CR	40	42	45	Ton/Day
ER	98	98	98	%
CXR	1.05	.98	.95	$/Ton

Capacity of Cubing, CR_{imps}

Efficiency of Cubing, ER_{imps}

Cost of Cubing, CXR_{imps}

Figure 3-16

Processing Unit (i = 3) Cuber

Product: Biomass Block - 2.5 cu.in. cube (p = 2)

Condition: Sloping (s = 2)
Poor Terrain

	m = 1	m = 2	m = 3	
CR	32	33	34	Ton/Day
ER	95	95	95	%
CXR	1.31	1.23	1.25	$/Ton

Capacity of Cubing, CR_{imps}

Efficiency of Cubing, ER_{imps}

Cost of Cubing, CXR_{imps}

Figure 3-17

Processing Unit (i = 3) Cuber

Product: Biomass Block - 2.5 cu.in. cube (p = 2)

Condition: Wet (s = 3)

	m = 1	m = 2	m = 3	
CR	24	25	26	Ton/Day
ER	85	85	85	%
CXR	1.75	1.64	1.64	$/Ton

Capacity of Cubing, CR_{imps}

Efficiency of Cubing, ER_{imps}

Cost of Cubing, CXR_{imps}

Figure 3-18

Transport Unit (i = 1) Truck-Trailer (20 tons)

Product: Sugarcane Billets (p = 2)

Condition: Flat (s = 1)

Distance: Avg. Range (d = 1)
20 miles round trip

	m = 1	m = 2	m = 3	
CT	160	180	200	Ton/Day
ET	95	93	90	%
CXT	.74	.72	.70	$/Ton

Capacity of Transport, CT_{impsd}

Efficiency of Transport, ET_{imp}

Cost of Transport, CXT_{imps}

Figure 3-19

Transport Unit (i = 1) Truck-Trailer (20 tons)

Product: Sugarcane Billets (p = 2)

Condition: Wet (s = 2)

Distance: Avg. Range (d = 1)
20 miles round trip

	m = 1	m = 2	m = 3	
CT	140	160	180	Ton/Day
ET	82	82	82	%
CXT	.98	.94	.90	$/Ton

Capacity of Transport, CT_{impsd}

Efficiency of Transport, ET_{imp}

Cost of Transport, CXT_{imps}

Figure 3-20

Transport Units (i = 1) Truck-Trailer (20 tons)

Product: Sugarcane Billets (p = 2)

Condition: Wet (s = 3)
Muddy

Distance: Avg. Range (d = 1)
20 miles round trip

	m = 1	m = 2	m = 3	
CT	106	120	140	Ton/Day
ET	82	81	80	%
CXT	1.36	1.30	1.25	$/Ton

Capacity of Transport, CT_{impsd}

Efficiency of Transport, ET_{imp}

Cost of Transport, CXT_{imps}

Figure 3-21

Plant Processing Unit (i = 1) Gasifier

Product: Wood Chips - 1 inch (p = 1)

	m = 1	m = 2	m = 3	
CP	127	131	135	Ton/Day
EP	30	29	28	%
CXP	30.00	29.00	28.07	$/Ton

Capacity of Plant Processing, CP_{imp}

Efficiency of Plant Processing, EP_{imp}

Cost of Plant Processing, CXP_{imp}

Figure 3-22

Plant Processing (i = 1) Gasifier

Product: Wood Chips - 2 inch (p = 2)

	m = 1	2	3	
CP	127	131	135	Ton/Day
EP	27	26	25	%
CXP	31.50	30.00	29.00	$/Ton

Capacity of Plant Processing, CP_{imp}

Efficiency of Plant Processing, EP_{imp}

Cost of Plant Processing, CXP_{imp}

Figure 3-23

Plant Processing (i = 1) Gasifier

Product: Wood Chips - 3 inch (p = 3)

	m 1	m 2	m 3	
CP	127	131	135	Ton/Day
EP	25	25	25	%
CXP	34.00	33.00	32.00	$/Ton

Capacity of Plant Processing, CP_{imp}

Efficiency of Plant Processing, EP_{imp}

Cost of Plant Processing, CXP_{imp}

Figure 3-24

Transport Unit (i = 2) Truck (20 tons)

Product: Wood Chips (p = 1)

Conditions: Flat (s = 1)

Distance: Average Range (d = 1)
20 miles round trip

	m = 1	m = 2	m = 3	
CT	160	180	202	Ton/Day
ET	95	95	95	%
CXT	.89	.84	.80	$/Ton

Capacity of Transport, CT_{impsd}

Efficiency of Transport, ET_{imp}

Cost of Transport, CXT_{impsd}

Figure 3-25

Transport Units (i = 2) Truck (20 tons)

Product: Wood Chips (p = 1)

Condition: Wet (s = 2)

Distance: Average Range (d = 1)
20 miles round trip

	m = 1	m = 2	m = 3	
CT	140	160	180	Ton/Day
ET	95	95	95	%
CXT	1.05	.98	.92	$/Ton

Capacity of Transport, CT_{impsd}

Efficiency of Transport, ET_{imp}

Cost of Transport, CXT_{impsd}

Figure 3-26

Transport Units (i = 2) Truck (20 tons)

Product: Wood Chips (p = 1)

Conditions: Wet (s = 3)
Muddy

Distnace: Average Range (d = 1)
20 miles round trip

	m = 1	m = 2	m = 3	
CT	106	120	140	Ton/Day
ET	90	90	90	%
CXT	1.36	1.30	1.25	$/Ton

Capacity of Transport, CT_{impsd}

Efficiency of Transport, ET_{cmp}

Cost of Transport, CXT_{impsd}

Figure 3-27

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