OFF-FARM PROCESSING: DEVELOPMENT OF A FORAGE COLLECTION SCHEDULING MODEL

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ABSTRACT

The collection of straw and grasses for use in various industries is expanding, as there is a need for material in both the traditional forage markets and in the bio-products and bio-fuel industries. Because these materials tend to be bulky and difficult to transport there is a need for managers to optimize the performance of their collection process.

The model focuses on two different types of collection, baled material and loose chops. The material is mowed, allowed to dry in field, and then collected with either a baler or a forage harvester. The model uses a combination of historical data and managerial inputs to compute the approximate costs of the material. The model also identifies the average and maximum delays involved in the collection of the material. These outputs allow a manager to identify areas where processing costs are high, and areas where there might be significant delays or excess capacity in the process.

The model was verified by comparing results to information that was collected from two different facilities. One facility dealt primarily with fresh forage, while the other dealt exclusively with sun-cured forage. The model was verified to within 15% of the actual data, however, with continued refining of the input costs the modeled results can be much closer to actual operating costs.

After verification, a number of scenarios were tested to determine the models' greatest sensitivities. The effects of changing fuel costs, labour costs, and the length of the working day were all investigated. It was found that the repair and maintenance costs had a larger effect then either the fuel or labour costs for most types of equipment. It was also found that the model was very sensitive to the capacity of the equipment.

For the model to provide an accurate representation of forage collection, the system must be adjusted to reflect the costs associated with a particular facility. After these adjustments are made, the operator can investigate the effects of changes on his/her particular operation.

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1. INTRODUCTION

The uses for biological materials are growing and include not only food (grains, oilseeds, and pulses), and feed (grasses, alfalfa, and green feed), but also industrial applications, such as pulp and paper, particleboard, ethanol production, fuel for heating, and building construction (Klassen, 1994). In addition, more biomass materials are being harvested or investigated for use in industry. These materials include corn stover (Turhollow and Sokhansanj, 2004), cotton stalks (Tatsiopoulos and Tolis, 2002), alfalfa, elephant grass (Berggren, 1993), reed canary grass (Nilsson, 1999; 2000; 2001), and ryegrass (Gorzell, 2001). This has lead to increased interest in the economical collection and transportation of these materials.

Biomass materials are generally lower in density, more variable, have a much shorter shelf life, and have higher storage costs than most industrial materials. While steel can last years when it is placed in storage, straws, grasses, and alfalfa can last as little as a few months. There are also time constraints in the collection of biological materials that are not applicable to plastics or steel. This leads to higher storage and transportation costs for biological materials.

A supply model allows the manager of a collection facility to predict the effects that various scenarios could have on their operation. For example, one could determine the effects of fluctuations in the price of fuel, a reduction in the amount of available labour, changes in the land base, inclement weather and changes to the capacity of equipment.

For the purposes of this thesis, the model has been confined to the collection of alfalfa for a cubing plant. However, the model can be adapted for use by managers collecting various other fiber-based materials.

The outputs of the final model are the fuel, labour, and other costs associated with harvesting the material.

1.1 Alfalfa Management

The yield of alfalfa is dependent upon the region in which it is grown and whether or not it has an adequate water supply. Saskatchewan is divided into three different soil zones, each of which have different characteristics. According to the Saskatchewan Forage Crop Production Guide (Saskatchewan Agriculture and Food, 2001), alfalfa yields in 2001 ranged from 3120 to 4136 kg/ha in zone one, 6378 to 7570 kg/ha in zone two, 5905 to 6910 kg/ha in zone three and 9953 to 13191 kg/ha under irrigation, for recommended varieties. (yields are expressed in dry weight basis). Most of the irrigated land in Saskatchewan is found in zone two. Zone two runs diagonally across the province from the Alberta border (between Lloydminster and Kindersley) to the southern border of the province. It includes the Saskatoon, Regina, Moose Jaw, and Estevan areas.

The highest quality cut of alfalfa is usually the first cut of the season. The hay industry uses quality attributes such as the protein content, the relative feed value, and the fibre content. The texture (hardness), stage of maturity, leaf content, and colour are also important in the grading and marketing of the forage. The hay should be free of weeds, mold and dust. (Saskatchewan Agriculture and Food, 2001) The first cut is generally taken when the field has reached about 10% bloom. This is usually about the third week of June, but varies depending on the variety and weather conditions. The last cut of alfalfa should take place in early autumn so that the plants can grow to a stage where it can withstand the cold and snow of winter. Mowing fields too late in the autumn can result in winter-kill and mean significant losses in the following year's crop. Therefore, this model allows the fields to exit the system at a date set by operator.

1.2 Collection and Transportation

In this model, the facility operator controls the production of alfalfa. This allows the acreage to be set constant and more easily balanced with respect to costs, labour, and fuel. It is possible to increase the acreage in the model in order to determine if it would be feasible to control more of the production.

This research included two different methods of collecting hay crops. The material can either be harvested using a mower and a forage harvester (fresh forage) or it can be left to dry in the sun and baled (sun-cured forage). Both methods are used on a limited basis in this model. An operator can set the system for use as a primarily fresh facility (fields beyond a specified distance are baled and the rest is harvested with a forage harvester) or a primarily bale facility (there are no forage harvesters in the system).

1.2.1 Harvesting fresh forage

Many cubing and pelleting facilities will use fresh or wet forage in the summer months. The fresh forage tends to produce cubes and pellets that are greener than the sun-cured (sun-dried) forages. The greenness of the cubes often relates directly to the price demanded. However, the fresh forage requires much more artificial drying than the sun-dried forage.

Fresh forage is first mowed and then collected by a forage harvester. The forage harvester chops the fresh forage and then blows it into a forage wagon. The wagons are then hauled to the cubing facility by truck.

The moisture content of fresh forage can be as high as 80% (w.b.), depending on the length of time the material is allowed to wilt prior to being collected with the forage harvester (Sokhansanj, 2000). Because wet forage has such a high moisture content, it is important that it be processed the same day that it is transferred to the facility. Wet forage can spoil very quickly under typical summer harvest conditions.

1.2.2 Harvesting and collection of dry forage

Harvesting dry forage consists of mowing the field, allowing the forage to dry in the sun, baling the hay, and then transporting the bales to the facility by truck. Fresh alfalfa is usually 70-80% moisture and it must be dried to approximately 13%(w.b.) prior to baling for safe storage (Sokhansanj, 2000).

There are three types of bales currently in use in western Canada; large round bales, small rectangular bales and large rectangular bales. Small rectangular bales are used in areas where people will be lifting the bales into place. The bales generally range in mass from 22 to 36 kg. Round bales became more common when farm sizes made small rectangular bales impractical for harvest and daily chores. Round bales are up to 2 m in diameter and 1.7 m long. They weigh approximately 680 kg, depending on the manufacturer of equipment. (Sokhansanj et al., 2000). Large rectangular bales are growing in popularity. They have the advantage of easier, more compact stacking than round bales. The large rectangular bales are also favoured for the production of double-compressed bales, as they can be sliced and compressed. Large rectangular bales weigh approximately 750 kg.

The use of sun-cured forage produces a more uniform, less costly, and less energy-intensive product. This also stabilizes the requirements of the processing facility. The use of bales allows for less traffic around the facility during the summer months and can create a forage inventory for a facility.

The baled forage is generally stored outside, on the farm, after it is baled. The outside of the bale is exposed to the elements and it protects the inside of the bale from the sun and rain. The bales are brought to the processing facility by truck as required. This eliminates the need for a lot of storage at the processing site. The bales are ground and mixed as part of the cubing process, allowing for the weathered and the unexposed hay to be mixed before cubing. Bales that are used for making compressed hay bales for export are often stored under cover to ensure that the bales are of uniform quality.

One important factor in the transportation of the bales is the size of the load allowed by the local department of highways. There are often load restrictions when the roads are wet from snowmelt or heavy rainfall. These restrictions may affect the transportation of bales from storage areas to the processing facility. The rest of the year, there are restrictions based on the type of road that is being traveled (primary, secondary, or municipal), the number of axles on the truck, and differences in local municipalities. The Saskatchewan Highways and Transportation weight restrictions are shown in Table 1.1.

Table 1.1 Typical weight restrictions for Saskatchewan roads (Saskatchewan Highways and Transportation, 2000)

Truck Type	Road Type				
	Primary (kg)	Secondary (kg)	Municipal (kg)	Winter Primary (kg)	Winter Sec. and Mun. (kg)
Straight truck 2 axles	16 350	13 700	13 700	17 250	15 500
Straight truck 3 axles	24 250	20 000	20 000	25 250	23 500
Straight truck with tandem steering	30 600	25 500	25 000	31 600	29 000
Truck and tandem pony	41 250	34 500	34 500	43 250	41 500
Truck and tridem pony	45 250	40 000	40 000	46 250	44 500
Truck and full trailer 5 axles	42 450	36 400	36 400	45 250	43 500
Truck and full trailer 6 axles	50 350	42 700	42 700	53 250	51 500
Truck and full trailer 7 axles	53 500	49 000	49 000	53 500	53 500
Tractor and semi-trailer 4 axles	31 600	28 200	28 200	33 500	33 500
Tractor and semi-trailer 5 axles	39 500	34 500	34 500	41 500	41 500
Tractor and semi-trailer 6 axles	46 500	40 000	40 000	46 500	46 500
A -C Train 6 axles	49 800	44 600	44 600	53 500	53 500
A -C Train 7 axles	53 500	49 000	49 000	53 500	53 500
A -C Train 8 axles	53 500	49 000	49 000	53 500	53 500
C Train 8 axles with approved dolly	60 500	54 500	54 500	60 500	54 500
B Train 7 axles	56 500	49 000	49 000	59 500	54 500
B Train 8 axles	62 500	54 500	54 500	62 500	54 500

There are also dimension regulations for shipping in Saskatchewan. Loads cannot be wider than 2.6 m, mirrors can extend an additional 200-mm, and tie-downs can extend an additional 100 mm. The maximum load height is 4.15 m. The maximum vehicle length is 25 m (Saskatchewan Highways and Transportation, 2000).

1.3 Cubing

Alfalfa cubes are formed through a densification process that binds the material together (see cubing process overview). Cubes range in size from 13 to 38 mm across, depending on the size of the die used to form the cubes. The cubes are usually 25 to 100 mm in length, depending on the process and the raw material properties. The resulting bulk density is approximately 550 kg/m^3 (Sokhansanj, unpublished). High quality cubes are bright green in color. They are hard enough to retain their shape during handling, yet soft enough that the livestock can chew them without difficulty.

1.3.1 Cubing process overview

The processes for creating fresh forage cubes and sun-cured cubes are very similar. For sun-cured cubes, the bales are brought into the processing facility, the twine is removed and they are loaded into a large tub grinder to break the long fibres into shorter fibres for the cubing process. At this point the process is identical to fresh forage cubes. The chops are pneumatically conveyed through a rotary drum drier to the cubing machine. Water is often added to condition the material just prior to the material entering the cubing machine. The combination of water, pectin, and protein in the material, along with the high temperatures and pressure used for extrusion, bind the cubes. After the material is pushed through the dies, the cubes are cooled and cured in a storage shed. The shed protects the cubes from the rain and sunlight.

The curing process can take two days during the winter months, or two weeks during the summer months. During curing, the cubes reach equilibrium moisture content with their surroundings and the binders in the cube become stronger. However, as time passes, the binders begin to deteriorate and the cubes become crumbly. They also begin to lose their color, becoming more brown than green (Khoshtaghaza et. al., 1995).

1.4 Models and Simulations

A model is a logical outline of how a system or process operates. Models tend to be useful for problems that are too complex for a simple spreadsheet analysis. These can include systems that are heavily dependent on time, random occurrences, and/or iterative calculations. The development of the model allows an operator to combine the calculations of a spreadsheet with the visual clarity of a flowchart.

There are two types of dynamic modeling, continuous and discrete event modeling. Continuous modeling involves the continuous flow of material through the model. These models recalculate values at regular intervals. For example, the accumulation of heat units for crop growth can be considered a continuous model. The calculation is required once in every 24-hour interval, knowing the daily maximum and minimum temperatures. The values do not stop accumulating. Discrete event modeling involves calculations being performed every time something in the model changes. For example, a field being ready to be harvested would trigger the recalculation of values such as labour costs. Time has no direct effect on the discrete event model. The model developed for this thesis is a combination of a discrete event model and a continuous model.

The purpose of simulation is to allow an operator to observe changes on a system at a fraction of the time and cost of experimentation. By modeling a system and simulating changes, an operator gains an intimate knowledge of the process. The construction of the model helps to ensure that the operator is aware of all the variables in the system

Imagine That Inc. (2005), the creators of the EXTEND© simulation software employed in this thesis, identified eight points to clarify the importance of simulation methodology.

> “A simulation program like Extend is an important tool that you can use to:
>
> - Predict the course and results of certain actions.
> - Understand why observed events occur.
> - Identify problem areas before implementation.
> - Explore the effects of modifications.
> - Confirm that all variables are known.
> - Evaluate ideas and identify inefficiencies.
> - Gain insight and stimulate creative thinking.
> - Communicate the integrity and feasibility of your plans.”

On a practical level, there are specific stages involved in the development of a simulation (Gilbert and Troitzsch, 2002) The modeler first designs the model. The modeler must find a way to simplify the process that they are attempting to simulate. This involves determining which information must be included and which must be left out. It also involves deciding how the process will flow and how an operator will interact with the model. The model is then built using either a package or a program of the modeler’s design. Following the construction of the simulation, it is tested and debugged by running scenarios. This verification allows the modeler to determine if the model is operating correctly. The model is then validated by comparing the results to either real world processes or to other models of the same process.

1.5 Software

The primary software used in the development of the model is EXTEND© (Imagine That Inc, San Jose, CA). EXTEND© was first marketed as a simulation software in 1988 (Krahl, 2002). The software is a graphical modeling tool that allows the operator to develop simulations of processes and manufacturing and supply chain scenarios. An operator uses the blocks in the software package to build a model of a process. (Refer to Appendix 5 for a description of the blocks used in this model.) The operator can then perform various what-if analyses in order to determine how different variables influence the process. EXTEND© tracks the flow of objects through the model. It also monitors the resources that are required to manage the objects, such as equipment, labour, money, etc.

EXTEND© can be used in two modes: ready to use graphical blocks and a C-like computer language with many built in functions. The graphical blocks carry out specific tasks such as activities, queues, decisions, input and output functions, and resource allocation. The C-like code, called Modl, interacts with the graphical blocks and databases. A model is created by dragging blocks from a library onto a worksheet, connecting the blocks, and then entering the appropriate data in the dialog boxes available for each block. EXTEND© can simulate processes in both discrete and continuous models. In discrete mode, the entire supply area is divided into units (fields in this model). Each unit moves from process to process with queues in between the processes.

The other software used in the development of the model is the spreadsheet EXCEL© (Microsoft Corporation, Redmond, WA).

1.6 Objectives

The objective of this thesis is to outline the development, verification and testing of a model that simulates the harvest and collection of forage from the field. The model is designed to be a managerial tool for the forage industry. A manager is able to balance the system, based on his/her facility history, and then run the simulation to determine how changes will affect the operation. The manager is then able to investigate the sensitivity of the delivered cost of forage to changes in the cost of fuel or labour, the effects of working longer or shorter days, the effects of increasing the capacity of their equipment, the effects of increasing their land-base, changes in crop maturity, changes in yield or other scenarios. The model allows the manager of a facility to compare various scenarios in order to identify delays in the system and plan for changes in the facilities operations. The ability of a manager to test scenarios and identify delays will help hem to minimize the costs associated with harvesting.

1.7 Organization of the Thesis

The remainder of this document is organized into the following sections:

(a) Literature Review – This section contains an overview of some of the work that has been done that either relates to the model or is in a similar area of study.

(b) Model Description – This section includes the development of the model, describes choices that were made with respect to the inputs, and includes a description of the model and how to operate it.

(c) Results and Discussion – This section includes the validation of the model. It also contains an analysis of a number of situations that may affect the operation of a facility. The final component of this section is a discussion of the aspects of the model that prove most sensitive to change.

(d) Conclusions

(e) Appendices – The appendices contain information such as a flowchart of the model, pictures of sections of the model, and definitions.

2. LITERATURE REVIEW

This section reviews models that have been developed by other researchers. Economic, collection, growth, soil, and drying models are all included.

2.1 Economic Models

Nilsson and Hansson (2001) investigated the collection of cereal straw and reed canary grass for use as fuel in district heating plants. The model developed accounted for the daily fuel use, soil moisture contents and crop growth and is presented in Figure 2.1. They found that the combination of a spring-harvested crop with a fall-harvested crop reduced the overall costs of heating by as much as 20% in areas where the price of straw is high. However, each case needs to be individually investigated as the cost depends on the price of the straw, the reed canary grass, other biomaterials (such as wood chips), and the price and availability of other fuels, such as oil. To do the analysis, Nilsson and Hansson used a variation of Nilsson's straw-handling model (SHAM). The 1999 model looked at various delivery alternatives to optimize the delivery of straw to heating plants with respect to costs and energy requirements (Nilsson, 1999). This model took into account the field drying, weather, infrastructure, and geographical information when determining harvesting methods and transportation requirements.

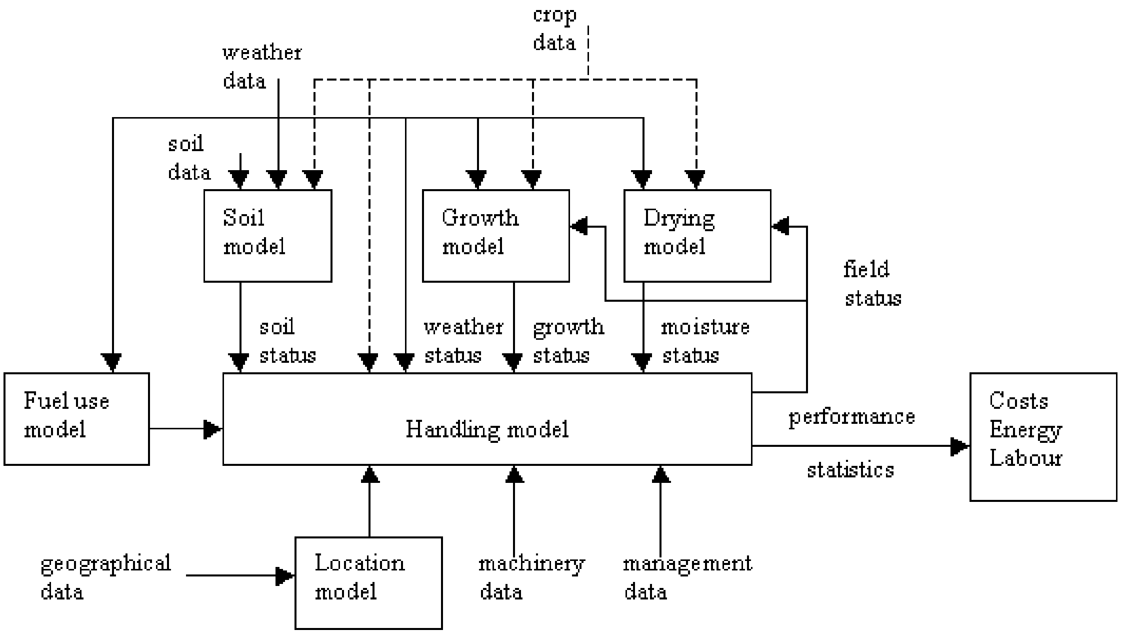


Figure 2.1 Overview of Straw Handling Model (SHAM), by Nilsson and Hansson (2001

Gorzell (2001) investigated the use of agricultural crop residue for the production of building materials. This investigation found that the high costs associated with collection, transportation, storage and adhesives generally placed the price of agricultural-based board above the price of wood-based products. This means that without subsidies the agricultural board companies must raise the price of their product to above the industry averages. This has led to the downfall of many processing facilities. For agricultural-based building materials to compete with wood-based products, it is necessary to reduce those costs. The companies that are producing agricultural-based building materials are finding niche markets where the properties of the agricultural-based board, such as the strength-to-weight ratio, appearance value, and low emissions, are preferable to wood-based products.

A similar study conducted in Sweden (Berggen, 1993) found that the raw material costs for agricultural materials were comparable to those for the production of birch for the pulp and paper industry. However, the capital costs associated with an agricultural-based facility were approximately double those of a birch-based facility. The logistics involved with the collection of agricultural materials and the dewatering of material meant that an efficient facility was able to produce less than one fourth of the pulp of a more traditional birch-based facility. Again, collection and transportation were shown to be the most significant factor in determining the economic feasibility of a facility.

Sourie and Rozakis (2001) analyzed the economic viability of bio-fuel production in France. The model (OSCAR©) localized the production of biomass in the most efficient farms. A price increase was assumed as incentive for producers to grow fuel crops instead of food crops; this led to the production of fuel crops on the better land instead of the more marginal land, increasing the yield of the crops. Because the OSCAR model optimized the location of production, it calculated the amount of land needed to provide fuel for the facility as lower than was actually required.

A report done by Oak Ridge National Laboratory (Turhollow et al., 1998) analyzed the costs of harvest and transport for hay and crop residues bales, hay and crop residue modules, and silage. A number of combinations of equipment were analyzed to determine the optimums for the movement of these materials. The cost of equipment, interest rate, maintenance (fuel, lube, oil), repairs, insurance, taxes, storage, and labour were included. While the lowest costs were associated with the use of silage; the costs of bales were not much higher. The Oak Ridge National Laboratory report was focused on the production of animal feed for local use, so the cost of drying the forage to a moisture content suitable for cubing was not taken into account.

Jenkins and co-workers (2000) analysed the equipment performance, costs and constraints of the collection of rice straw for industrial applications. They analyzed a system where the straw was baled in the field and then transported to storage areas until it was required for processing. Their systems used small rectangular bales and two types of large rectangular bales. The basis of their study was a survey completed by 84 growers of rice. Calculations were based on the “average” grower. Time and motion studies on operations such as raking, swathing, baling, roadsiding, loading, transportation and unloading were also conducted. It was determined that improvements in storage, straw yields, and equipment mobility would be required if rice straw was to be used for industrial purposes. The improvements reportedly increased the reliability and quality of the straw supply.

2.2 Transportation Models

The models in this section deal with the location of the facility, the movement of trucks and equipment, and the unloading of trucks at the facility. These are all individual aspects of the transportation of agricultural materials. The catchment area is the land from which a facility harvests its material. The transportation models affect how the equipment moves both in the field and on the road. The unloading model refers to how the trucks are unloaded at the facility.

2.2.1 Catchment Areas

Processing facilities are generally established in areas where there is enough available material at a cost low enough to provide the investors with an adequate rate of return. There are also considerations as to labour availability, incentives from communities, road and rail access, and other process-specific considerations, such as available water and costs associated with provided electricity (Jenkins et al., 1983).

Each processing facility brings in raw product from an area encircling the facility. Within this area, there may be a few central storage locations, around each of which is a catchment area. In Saskatchewan, most roads run in a straight line north/south or east/west. The only barriers to this type of movement would be bodies of water and towns.

The catchment area for a facility is based on a few different factors. The area in which it is economically feasible to collect material varies, depending on the capacity of the facility, the value of the product being made, and the value of the raw material. If a facility is already in operation in one area and the price of the raw material begins to rise, it may be more economically feasible to bring in material from a further distance than it would be to collect material within the original catchment area.

Nilsson (2000) determined the radius of the catchment area using

$$R_j = \left(\frac{n_j S_j}{100\pi Y_S \Phi_j} \right)^{\frac{1}{2}}, \qquad \textbf{(2.1)}$$

where:

R_j = radius of the circle around storage site j (km),

n_j = number of sectors of the circular area around storage area j,

S_j = supply of material in the storage area j (t),

Y_s = average yield of material (t/ha), and

Φ_j = the fraction of the circle occupied by product fields (percentage).

2.2.2 In-field harvesting models

The in-field models are essentially concerned with optimizing the movement of the equipment around the field in order to minimize the number of hours spent in each field. This may include mowing and baling, as well as the in-field transportation of bales to a site at the edge of the field for collection. Hunt (1986) described a variety of in-field models, including a continuous model (back and forth with turn strips at each end), a circuitous model (the equipment spirals inward to the center of the field), and a headland pattern (the equipment moves along two opposing edges of the field and turns along the other edges).

2.2.3 Field-to-storage models

Field-to-storage models include the movement of bales from the edge of the field to a general storage facility and then from the storage facility to the production facility.

Nilsson (2000) describes the distance between one field and another field or storage area as

$$d_{ij} = \tau\left(\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2\right)^{\frac{1}{2}}, \qquad \textbf{(2.2)}$$

where:

d_{ij} = distance from field i to storage are j (km),

τ = real transport distance in relation to straight line distance (unitless),

x_i, y_i = coordinates of field i, and

x_j, y_j = coordinates of field j.

2.2.4 Unloading Models

Berruto and Maier (2001) compared a segregated BATCH unloading method to a traditional FIFO (first in, first out) method for the unloading of different grains and oilseeds. The BATCH method sorts the trucks based on the material they are carrying. The FIFO method unloads the trucks in the order that they arrive at the facility. When the elevator was operating at capacity, the BATCH method shortened the average wait time by as much as 27%; however, at levels less then 75% of capacity the FIFO method was faster. Berruto et al., (2003) modeled the flow of material into a commercial elevator from nine farms. Their goal was to minimize the amount of time required to service each truck at the elevator. The effects of increasing equipment capacity or numbers as well as the impact of weather conditions and yield variability were investigated. This model dealt with single-harvest grains and oilseeds rather then multiple harvest forages and grasses.

2.3 Growth Models

There are growth models available for calculating the development of plants. One such model is used in EPIC©, a computer model that was developed by the United States Department of Agriculture, Agricultural Research Service, Soil Conservation Service, and Economic Research Service to simulate soil erosion (Meinardus et al., 1998). The daily heat accumulation for the crop is

$$HU_k = \frac{(T_{mx,k} - T_{mn,k})}{2} - T_{b,j}, \qquad \textbf{(2.3)}$$

where:

HU_k = accumulation of heat units on day k (cannot be negative),

$Tmx,_k$ = maximum temperature on day k (deg C),

$Tmn,_k$ = minimum temperature on day k (deg C), and

$Tb,_j$ = temperature for crop j below which there is no growth (deg C).

and the relative maturity of the crop, as calculated in EPIC, is

$$HUI_j = \frac{\sum_{k=1}^{i} HU_k}{PHU_j}, \qquad \textbf{(2.4)}$$

where:

HUI_j = heat unit index, an indicator of the maturity of crop j (0 to 1, unitless),

HU_k = heat units accumulated on day k, and

PHU_j = potential heat units required for the maturation of crop j.

2.4 Soil Models

The primary concern of the soil model for a harvesting project is the ability of the equipment to traverse the field without damaging the plants or getting stuck.

The moisture state of any soil is a function of the evapotranspiration, rainfall, irrigation, runoff, and drainage (Hunt, 1986). This relationship is shown mathematically as

Moisture State (N) = moisture state (N-1)

+ rainfall (N)
+ irrigation (N) **(2.5)**
- evapotranspiration (N)
- runoff (N)
- drainage(N)

where:

N = the day, and all terms are in units of mm of moisture.

Evapotranspiration is a function of temperature and relative humidity. Runoff is a function of rainfall, topography and soil structure. Drainage is the amount of water that flows through the soil. It is a function of the soil type and present moisture content. It is also necessary to account for snowfall in the precipitation. This would include an estimate of the melting rate, and evaporation estimation. This might be accomplished by assuming a field is at field capacity with no remaining snow as of a specified date.

Forage operations do not need to be halted for soil moisture conditions unless the field becomes too moist for the equipment to traverse.

2.5 Drying Models

The drying of alfalfa is based on the temperature and humidity of the environment, the size of the swath or windrow that the material is lying in, and the properties of the material itself. The initial moisture content of the cut alfalfa is approximately 80% (w.b.) (Sokhansanj, 2000) and it is necessary to dry it to less then 20% (w.b.), before it can be baled (Sokhansanj, 2000).

Rotz and Chen (1985) proposed a drying model for alfalfa in a field environment. The drying model was an exponential model relating the equilibrium moisture content to the initial and final moisture content given by,

$$\frac{M - M_e}{M_o - M_e} = e^{-DR(T)}, \qquad \textbf{(2.6)}$$

where:

M = moisture content (decimal or percent basis),

M_e = equilibrium moisture content (decimal or percent basis),

M_o = initial moisture content (decimal or percent basis),

DR = drying rate (h^{-1}), and

T = time (h)

There is a term in the model referred to as the drying rate (DR). An equation for the drying rate was calculated based on experimental data, and is given by

$$DR = \frac{SI(1 + 9.30AR) + 5.42DB}{66.4SM + SD(2.06 - 0.97DAY)(1.55 + 21.9AR) + 3037}, \qquad \textbf{(2.7)}$$

where:

AR = application rate of chemical solution (g of solution/g of dry matter),

DAY = 1 for first day, 0 otherwise,

DB = dry bulb temperature (ºC),

DR = drying rate (h^{-1}),

SD = swath density (g/m^2),

SI = solar insolation (W/m^2), and

SM = soil moisture content (% d.b.)

The equation uses dry bulb temperature as one of the factors, as opposed to vapour pressure because information on dry bulb temperature is more readily obtained.

2.6 Other Information

Hansen et al., (2002) used modeling to determine where the delays exist in a sugar cane harvesting system. Their concern was that delays lead to a drop in product quality. For forage-based systems, these types of delays are not as critical because some delay is needed after mowing in order to dry the material before being collected. The more critical delays are weather based. For example, forage should not be rained on between mowing and baling. However, once the material has been baled it is often stored outside, and the quality factors are dealt with by mixing the hay for the final product.

There have been a number of research papers focusing on using crop residues as a secondary revenue stream for agricultural producers. These products tend to have very low value in and of themselves, however, as markets expand their value will likely increase. Klassen (1994) investigated the use of straw from cereal crops in the production of pulp and paper, ethanol production, heating, and building construction. Tatsiopoulos and Tolis (2002) investigated the collection of cotton stalks for energy production. Because these stalks are usually burned, this would reduce the amount of soot and greenhouse gases in the atmosphere after harvest. There was also the potential for benefits such as employment for people after the cotton seed harvest, and the removal of parasites that can live in the dead stalks.

Turhollow and Sokhansanj (2004) simulated the collection of corn stover for use as a bio-fuel. Their model focuses on a crop that is harvested once each season as opposed to the multiple harvests available for alfalfa and grasses. EXTEND© was also used in the development of their models.

2.7 Summary

Models have been used to investigate a number of different facilities. These models often deal with single aspects of collection of the material, such as unloading or transportation. Other models investigate the collection of material using the facility demand as a key component. None of these models in the reviewed research have been developed as a management tool for the alfalfa industry.

3. MODEL DESCRIPTION

This model is intended as a management tool for the managers of alfalfa dehydration facilities and can be adapted for use by other fiber-based industries. The information required to operate this model is easily available to the managers. It can also be adjusted in order to change the crop, fields, year, equipment, and other factors. The model can be used for the collection of any type of material that is either baled or harvested as forage. For facilities where both forage harvesters and balers are used, the operator can set a distance away from the facility where closer fields are harvested with a forage harvester and further fields are baled.

The flowchart of the model in Appendix 1 should be referred to while reading about the model. The flowchart has been simplified by removing many of the calculation steps and incorporating only the decision-making components.

For this model to be useable for a number of facilities, some adjustments were made to the set-up and to the operation. The model was separated into 3 different aspects. The three parts consist of the worksheet (EXCEL©), the notebook (EXTEND©) and the programming (EXTEND©).

3.1 Cost Equations

This model uses cost as the common output value for all operations. This allows a manger to compare each operation and each component of an operation on a common basis.

There are two types of costs associated with the harvesting of agricultural materials; fixed costs and operating costs. Fixed costs are costs that must be paid even if a facility does not operate in a given year. The fixed costs include the capital recovery cost ("equipment cost" in the model) and other fixed costs ("other costs" in the model). The capital recovery cost is defined as

$$\text{Fixed} = \left[I_O \left(\frac{r}{1-(1+r)^{-n}} \right) - SV_n(r) \right] + \text{Other}, \qquad \textbf{(3.1)}$$

where:

Fixed = fixed costs associated with the system,

I_O = initial cost of a piece of equipment,

n = time (year),

Other = other fixed costs (insurance, taxes, etc.),

r = rate of return (decimal),

SV = salvage value of equipment.

The model does not include an interest rate or a salvage value, however the cost of equipment can be amortized over a given number of years.

Operational costs are those costs directly related to the action of harvesting the material. The operational costs are described as follows;

Operational Cost = (Repair and Maintenance) + Fuel + Labour, **(3.2)**

where all costs are for the hours that a piece of equipment is operating.

The fixed and operational costs are combined as follows;

Total Cost = Σ Fixed Costs + Σ Operational Costs, **(3.3)** where the costs for all pieces of equipment are included.

In this model results are generally stated on a $/tonne or $/bale basis. The $/tonne value is based on the moisture content of the yield reported. The $/bale option was included to allow facilities which purchase bales to use that comparison.

3.2 Data requirements

Weather data: Weather data for this project were obtained from Environment Canada through their website, www.weatheroffice.ec.gc.ca (Environment Canada, 2005). There are weather stations at various locations around Canada that provide rainfall and temperature records to Environment Canada.

Crop data: This section includes the data specific to the crop. This may include the information about maturation rates, desired maturation prior to harvest, requirements for water, and sunlight as well as information about the solar drying of the crop.

Machinery data: This section includes the types of machinery available. Each piece of machinery requires information about fuel use, capacities, and operator requirements. The production of alfalfa bales requires cutting devices (swather, mower), balers, tractors to run the machinery, and truck/trailer equipment. Each of these pieces of equipment requires an operator and has characteristics associated with fuel use, production capacities and operator requirements. The model uses the averages for all machines of a specific type. For example, the capacities of all the available mowers are averaged by the manager and that capacity is input to the model. The machinery inside of the processing facility will not be discussed.

Management data: This section contains the information for which the manager is responsible. This includes the amount of material required for the processing facility, whether or not the crew works overtime, their wages and other such information. This also includes the purchase of any material that is outside of the scope of the model.

Geographical data: The geographical data include the distance that is traveled in order to collect the biomaterial, any peculiarities such as large bodies of water, and any other information relating to the topography of the region. It also includes the location of collection and storage sites in relation to the processing facility.

3.3 Model Part 1 - EXCEL© Spreadsheet

The first section of the model is an EXCEL© spreadsheet. The spreadsheet calculates machine data for the operator to input to the model. The calculations were done separate from the model so that if a manager has data that are specific to their equipment they can use that information. However, if the manager does not have that information available he/she can use the machine data based on ASAE standards D497.4 and EP496.2 (ASAE, 1999).

The spreadsheet is shown in Appendix 2 and is also on the enclosed disk.

3.4 Model Parts 2 and 3 - EXTEND© Software

The remaining two sections of the model have been developed in EXTEND©. EXTEND© is a graphical modeling software package, developed for performing "what-if" analysis on discrete dynamic systems. The model is included on the enclosed disk.

The notebook is essentially the user-interface for the system. All of the information that needs to be changed easily was linked to this section. This means that people without a good understanding of the software can adjust the system to their needs. The majority of the remaining report is written as if the user is only using the notebook and the worksheet. Appendix 3 contains the notebook in its entirety. Sections of the notebook are also shown as required in the thesis.

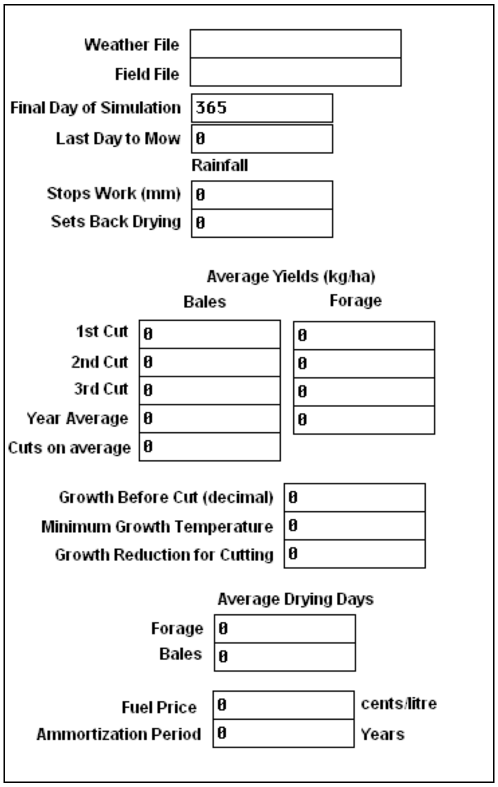
The third section is the model itself. This is the area where changes to the calculations or the model set-up need to be made. To make changes in this section requires a better understanding of the program and the equations used in its creation. Sections of the model are shown where appropriate in the remaining chapter. For the entire model refer to Appendix 4 and the enclosed disk. Appendix 5 contains information on the various blocks used in the model and a glossary of terms.

3.5 Notebook Section

This section deals with the information collected by and displayed in the notebook section of the model. This includes the collection of information and the outputs of the model.

3.5.1 Information collection

The first sections of the notebook are for information collection. This includes information on weather, fields, equipment, crops and all other data needed to operate the model. The information collection consists of three pages of information. Figure 3.1 shows the first page of the notebook.



Weather File

Field File

Final Day of Simulation 365

Last Day to Mow 0

Rainfall

Stops Work (mm) 0

Sets Back Drying 0

Average Yields (kg/ha)

	Bales	Forage
1st Cut	0	0
2nd Cut	0	0
3rd Cut	0	0
Year Average	0	0
Cuts on average	0	

Growth Before Cut (decimal) 0

Minimum Growth Temperature 0

Growth Reduction for Cutting 0

Average Drying Days

Forage 0

Bales 0

Fuel Price 0 cents/litre

Ammortization Period 0 Years

Figure 3.1 The first page of the information collection in the notebook, managerial information.

The first two rectangles are the weather data and the field data file inputs. The field data consist of the size of the field (ha) and the distance by road from the main site (km). The field data should begin with a row of zeros. This should be followed by a field size and distance for each field. The file should then be filled with zeros to a total of 300 rows. This was done so that facilities with up to 300 fields can operate the model without large adjustments. The format of the field data file, using the simulated farm data, is shown in Table 3.1. A field with a size of zero hectares is disposed of at the beginning of the simulation.

Table 3.1 Simulated facilities field data.

Field Distance (km)	Field Size (ha)	Row
0	0	1
0.9	129	2
3.2	23	3
2.8	65	4
0.4	60	5
1.6	61	6
6.4	51	7
5	100	8
0	0	9
.	.	.
.	.	.
.	.	.
0	0	300

Note: the Row column is not part of the field file.

The weather data consist of the maximum daily temperature, minimum daily temperature, and rainfall. These data are available through Environment Canada (www.weatheroffice.ec.gc.ca) or can be adapted from any similar source. If the user does not input a field file, or a weather file, the computer will prompt the operator for the file names and locations. Table 3.2 shows a portion of the weather data for the simulated farm. The weather data must begin at a day prior to any crop growth. In Saskatchewan, the weather data should begin before April 1st to ensure that even very warm springs are covered in the model.

Table 3.2 Sample of weather data for the simulated farm. Weather data for the outlook area obtained from Environment Canada (online).

Daytime High (ºC)	Daytime low (ºC)	Precipitation (mm)	Date
5.5	-2.7	0	1-Apr-99
7.1	-5.1	0	2-Apr-99
5.3	-3.3	4.5	3-Apr-99
-0.1	-3.2	0.6	4-Apr-99
8.2	-4.8	0.2	5-Apr-99
10.2	-1	0	6-Apr-99
17	-0.9	0	7-Apr-99
20.5	1.3	0	8-Apr-99
9.9	2.9	0.2	9-Apr-99
8.6	0.4	0	10-Apr-99
11.8	-2.3	0	11-Apr-99
18.5	1	0	12-Apr-99
10.6	1	0.2	13-Apr-99
10	-0.3	0	14-Apr-99
9.5	-1.9	0	15-Apr-99
9.6	-4	0	16-Apr-99
19.9	2.5	0	17-Apr-99
13.3	3.1	0	18-Apr-99
9.9	0.2	3.8	19-Apr-99
12.3	3.4	2.2	20-Apr-99
11.5	0.4	0	21-Apr-99
13.5	-1.2	0	22-Apr-99
18.4	-1	0	23-Apr-99
21.9	5.8	0	24-Apr-99
21.8	4.3	0	25-Apr-99
16.1	8.3	0.6	26-Apr-99
20.6	7.1	0	27-Apr-99
17.2	5.1	0.6	28-Apr-99
11	4.6	1.4	29-Apr-99
16.2	3.3	0.2	30-Apr-99
.	.	.	.
.	.	.	.
.	.	.	.

Note: This is a sample of the weather data. The weather data actually contains information for over 250 days. The Date column is not part of the weather file

The final day of simulation and final cutting day inputs are located directly below the field and weather file inputs in the notebook. The final day is the last day that the simulation will run. It must be less then or equal to the number of days in the weather file. This prevents the model from stalling when it has used all of the information in the weather file. The final cutting day is the last day on which mowing can occur. All other operations can proceed past this day. The days must be converted to a numerical value that corresponds with the weather data. For example, if the weather file contains data for January 1 through December 31, 2003, then day 1 is Jan. 1, day 2 is Jan. 2, … day 365 is December 31. If the manager wants to stop mowing fields after August 31, 243 will be input as the final cutting day.

The next series of inputs is the rainfall information. This includes the amount of rainfall that stops work for the day and the amount of rainfall that sets back the drying by one day. (A field that needed 2 days to finish drying will now require 3 days if the "Sets back Drying" amount of rain falls.) The rainfall levels are set based on the operator's experience.

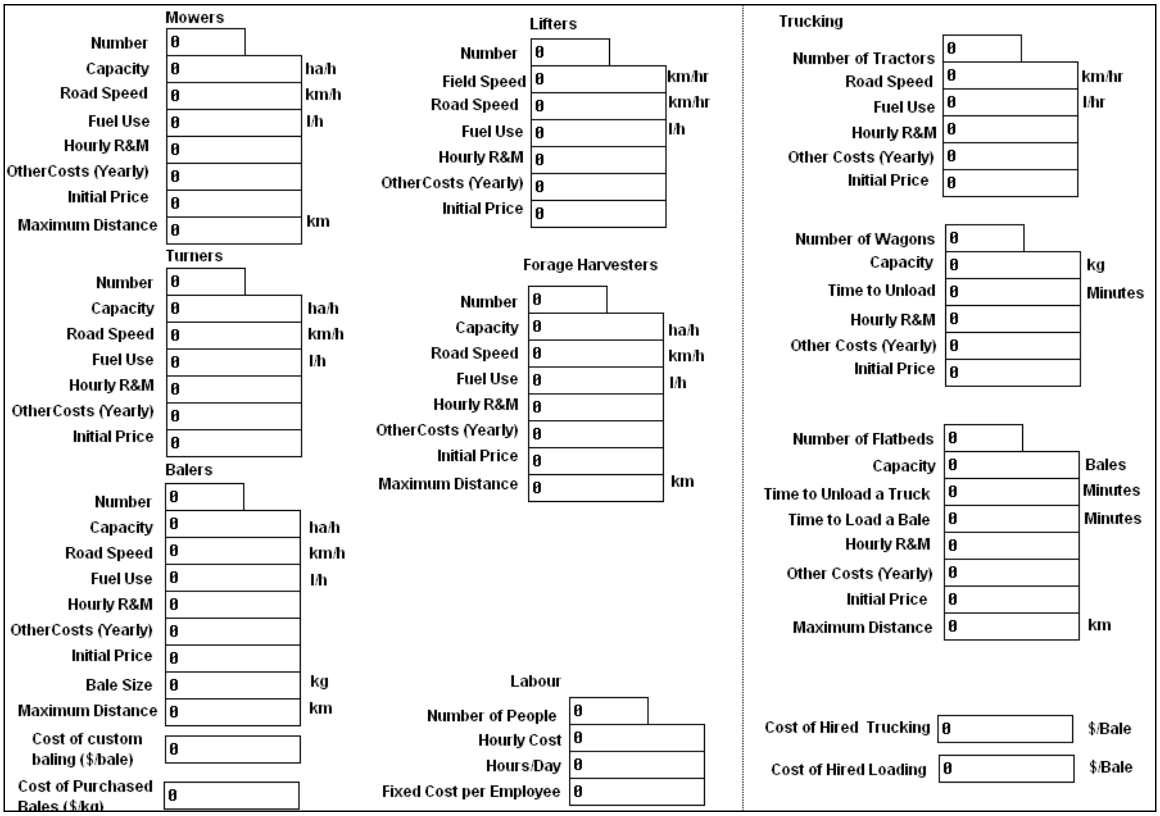
The yields follow the rainfall information. The yields are either baled or wet forage. The yields can be separated by cut or an average yield can be used. The number of cuts in a year is also included. The moisture content of the yield is left to the manager's discretion. However, the bale size and forage wagon capacity must correspond to the moisture content of their respective yield. The outputs will also be based on the moisture content of the yield. The average yield is available through Saskatchewan Crop Insurance Corporation, or a similar local organization, specific to the year and area of the simulation. A manager can also use the facilities recorded yields for each cut. Using the historical yields, combined with the historical weather data, compensates for not including rainfall in the growth equation.

The next series of inputs are crop specific. This includes the growth before cut, minimum growth temperature, growth reduction for cutting, and drying information. Adjusting these numbers can change the model to operate for other forage crops. Growth before cut corresponds to the heat unit index in Equation 2.4. The minimum growth temperature corresponds to the minimum growth temperature in Equation 2.3. The growth reduction for cutting is the value that is subtracted from the heat unit index because the field has already been harvested. If these numbers are adjusted, the operator should check the date of the first harvest to ensure that the model is operating properly.

The average drying days are the number of days that are usually left between the process of mowing and baling or using the forage harvester. The operator inputs the average number of drying days for each process. The operator can adjust the number of drying days to be most applicable to their particular equipment. This is important because crushers and macerators can increase the field drying rate dramatically (Patil, 1993).

The final two inputs in this section are the fuel price and the amortization period. The fuel use and fuel price are on a volumetric basis. Fuel is sold on a volumetric basis, therefore, this is the most useful unit for most managers. An operator can use equipment that operates on diesel, gasoline, or LPG. The model assumes that all pieces of equipment operate on the same type of fuel. These are used to calculate the costs of the process and to amortize the equipment costs over a fixed period.

The next page of data is the machine specific data, see Figure 3.2.



Mowers

Number	0	
Capacity	0	ha/h
Road Speed	0	km/h
Fuel Use	0	l/h
Hourly R&M	0	
OtherCosts (Yearly)	0	
Initial Price	0	
Maximum Distance	0	km

Turners

Number	0	
Capacity	0	ha/h
Road Speed	0	km/h
Fuel Use	0	l/h
Hourly R&M	0	
OtherCosts (Yearly)	0	
Initial Price	0	

Balers

Number	0	
Capacity	0	ha/h
Road Speed	0	km/h
Fuel Use	0	l/h
Hourly R&M	0	
OtherCosts (Yearly)	0	
Initial Price	0	
Bale Size	0	kg
Maximum Distance	0	km
Cost of custom baling ($/bale)	0	
Cost of Purchased Bales ($/kg)	0	

Lifters

Number	0	
Field Speed	0	km/hr
Road Speed	0	km/hr
Fuel Use	0	l/h
Hourly R&M	0	
OtherCosts (Yearly)	0	
Initial Price	0	

Forage Harvesters

Number	0	
Capacity	0	ha/h
Road Speed	0	km/h
Fuel Use	0	l/h
Hourly R&M	0	
OtherCosts (Yearly)	0	
Initial Price	0	
Maximum Distance	0	km

Labour

Number of People	0
Hourly Cost	0
Hours/Day	0
Fixed Cost per Employee	0

Trucking

Number of Tractors	0	
Road Speed	0	km/hr
Fuel Use	0	l/hr
Hourly R&M	0	
Other Costs (Yearly)	0	
Initial Price	0	

Number of Wagons	0	
Capacity	0	kg
Time to Unload	0	Minutes
Hourly R&M	0	
Other Costs (Yearly)	0	
Initial Price	0	

Number of Flatbeds	0	
Capacity	0	Bales
Time to Unload a Truck	0	Minutes
Time to Load a Bale	0	Minutes
Hourly R&M	0	
Other Costs (Yearly)	0	
Initial Price	0	
Maximum Distance	0	km

Cost of Hired Trucking	0	$/Bale
Cost of Hired Loading	0	$/Bale

Figure 3.2 The second and third pages of information collection in the notebook, equipment information.

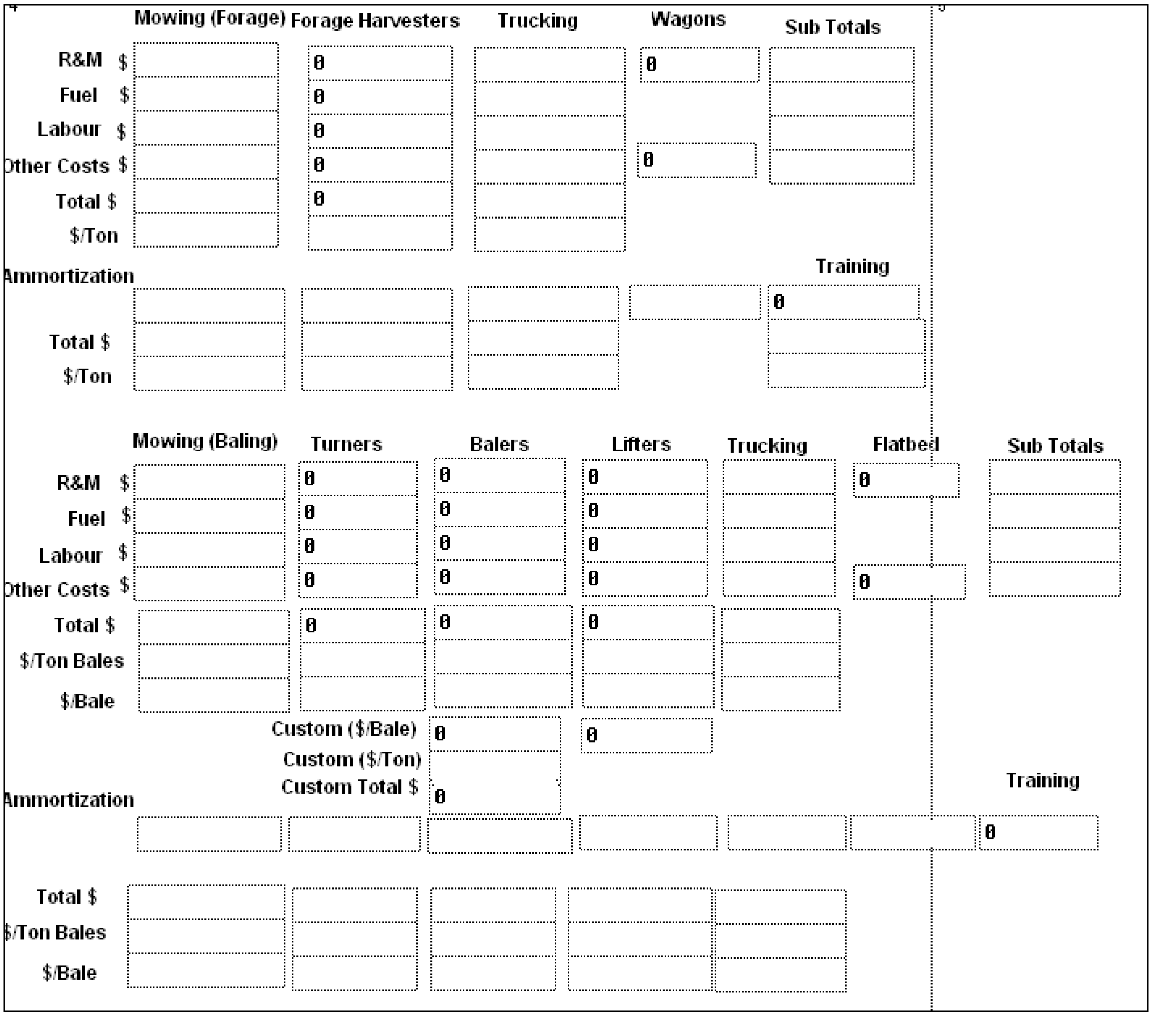
This section of the notebook is specific to the system in which the model is being used. The system is set to incorporate mowers, turners, forage harvesters (and wagons), balers, flatbeds, and trucks (just the tractor). The equipment can be either used in-house or custom harvesters can be hired. The equipment data can be calculated in the worksheet or can be based on the operators' experience. There is also personnel information included in this section of the model, including average hours in a working day, average wages (including benefits), and training costs. The model assumes that the collection of the material is a seven-day a week process. The average duration of work is an average over the course of a week. For example, a facility normally operates 14-hour days, 5 days each week, for a total of 70 hours per week. This means that, on average, the facility does 10 hours of work each day. Therefore, the average hours should be set at 10.

The Farm Machinery Custom and Rental Rate Guide, produced by Saskatchewan Agriculture, Food and Rural Revitalization (2004), can be used to either assist in calculating equipment rates and costs or it can give the rates for custom harvesting or transporting.

It is important to note that the calculations require values in all of the fields in order to be completed. A blank field results in incomplete calculations. However, a value of 0 is enough to complete the calculations.

3.5.2 Outputs

The outputs are generated in the sections shown in Figure 3.3. This section is located below the input section of the notebook.



	Mowing (Forage)	Forage Harvesters	Trucking	Wagons	Sub Totals
R&M $		0		0	
Fuel $		0			
Labour $		0			
ther Costs $		0		0	
Total $		0			
$/Ton					

	Mowing (Forage)	Forage Harvesters	Trucking	Wagons	Training
mmortization					0
Total $					
$/Ton					

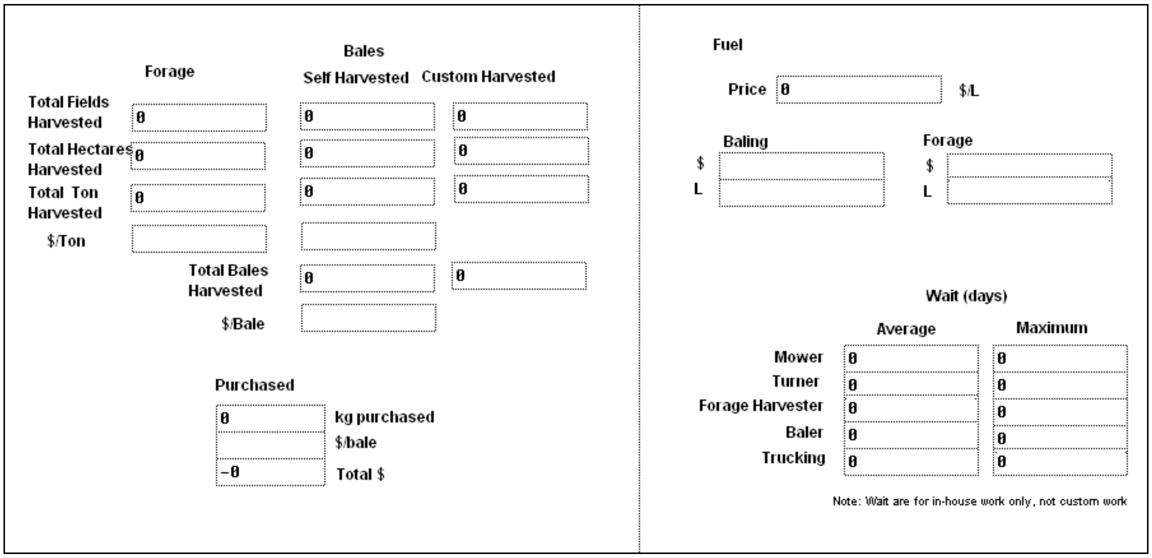
	Mowing (Baling)	Turners	Balers	Lifters	Trucking	Flatbed	Sub Totals
R&M $		0	0	0		0	
Fuel $		0	0	0			
Labour $		0	0	0			
ther Costs $		0	0	0		0	
Total $		0	0	0			
$/Ton Bales							
$/Bale							
Custom ($/Bale)			0	0			
Custom ($/Ton)							
Custom Total $			0				

	Mowing (Baling)	Turners	Balers	Lifters	Trucking	Flatbed	Training
mmortization							0
Total $							
/Ton Bales							
$/Bale							

Figure 3.3 The first page of outputs of the model, cost breakdowns by process and type.

The outputs show the cost/bale, cost/kg, and total cost for each step of the operation. They also show the total labour, fuel, repair and maintenance and other costs for each operation. Capital costs are also taken into account if they have been included in the information.

Instead of running an optimization on the system, this model highlights the delays in the system (see Figure 3.4). This allows the operator to adjust the equipment or labour useage in order to shorten lengthy delays or to make sure that there are some delays in the system (a delay of 0 days could indicate that there are too many pieces of that type of equipment).



	Forage	Bales Self Harvested	Custom Harvested
Total Fields Harvested	0	0	0
Total Hectares Harvested	0	0	0
Total Ton Harvested	0	0	0
$/Ton			
Total Bales Harvested		0	0
$/Bale			

Purchased

0	kg purchased
	$/bale
-0	Total $

Fuel

Price 0 $/L

Baling		Forage	
$		$	
L		L	

Wait (days)

	Average	Maximum
Mower	0	0
Turner	0	0
Forage Harvester	0	0
Baler	0	0
Trucking	0	0

Note: Wait are for in-house work only, not custom work

Figure 3.4 The second page of outputs of the model, totals and delay outputs.

The model also outputs a graph that shows when mowers, forage harvesters, balers and trucks finish each field. The graph does not distinguish between cuts but simply tallies the total number of fields that the equipment has harvested. The graph also provides a table of the data. This graph is useful in visualizing the movement of the fields through the system. It is shown in Appendix 3. The graph is not part of the notebook. It is a separate window that appears after every run.

3.6 Model

This section deals with the description of the model's components. The generation of fields and weather in the model are discussed as well as the various loops that the fields pass through.

Most of the loops in the model are equipment loops. A basic equipment loop is shown in Figure 3.5. The field enters the loop (A) and waits in a queue (B) until the appropriate equipment and labour is available. The rainfall is checked (C). If there is too much rain to work that day, the resources are released (1D), the field is delayed for 24 hours (1E), the priority of the field is increased (1F), and the field is sent back to the beginning of the loop (1G). If it is dry enough to work, the field size and distance are read (2D), the delay is calculated, the field is delayed (2E), and the resources are released (2F). The field is counted (2G) for use in the graph, and the priority is set to low (2H). The field is then passed on to the next appropriate loop (2I).

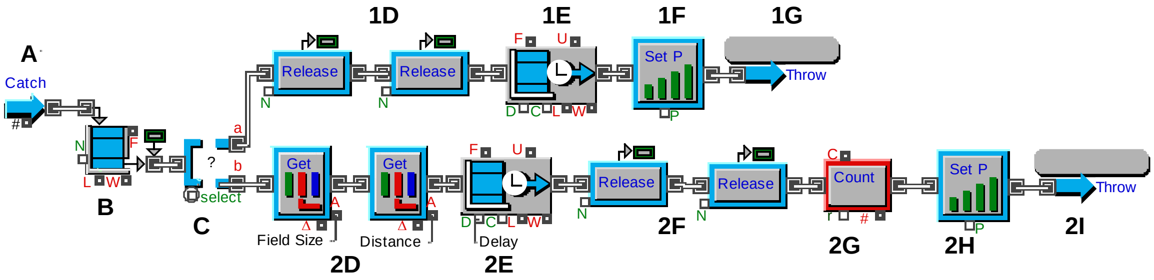


Figure 3.5 A basic equipment loop in this model.

The remainder of this chapter shows the loops as flowcharts. The model of each loop is included in Appendix 4.

3.6.1 Weather generation

The weather information used in this model are historical weather data. This allows a manager to compare operating conditions on a dry year vs. a wet year. As the days pass through the model, the weather file is called upon for information on the rainfall and the high and low temperatures. The temperature data are used in the growing loop to calculate the maturity of the crop.

The rainfall data are used for the following:

(a) a weighted average of the 3-day rainfall to determine if it is too wet to work (for use in the process operations later on); and

(b) a comparison to determine if the crop will dry on a given day, if the drying has been delayed due to rain, or if drying has been set back a day due to high rainfall.

The weather generation loop is shown in Figure 3.6. The "day" is generated by the model. The model assigns the maximum temperature, minimum temperature and precipitation to the "day" as read from the weather data file. The maximum and minimum temperatures are then read and sent to the appropriate sections of the model for calculations. The precipitation is read and sent to the "Precip Day 1" input of the three-day rainfall average calculation (shown in Appendix 4, Delay Calculations). The "day" is delayed for 24 hours, the precipitation is read again and is sent to the "Precip Day 2" section of the three-day rainfall average calculation. The "day" is again delayed for 24 hours. The precipitation is then read and sent to the "Precip Day 3" section of the three-day rainfall average calculation. At that point the "day" exits the model.

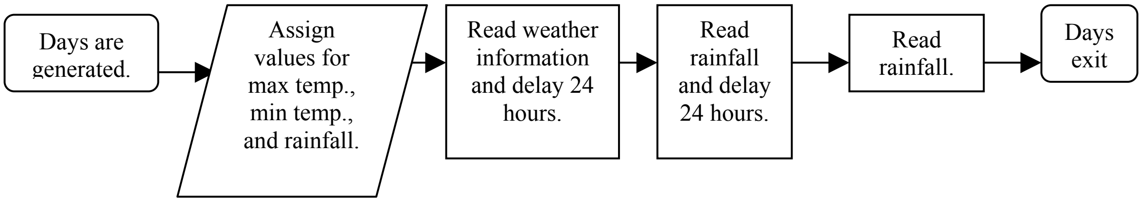


Figure 3.6 The weather generation loop.

3.6.2 Field generation

The field generation loop is shown in Figure 3.7. The model generates all of the fields on day zero. The fields are generated and then the field size and distance are read from the file. The attributes "cut" and "cycle use" are also set in this section. "Cut" refers to how many times the field has been mowed and is discussed further in the growing section. "Cycle use" is used in sections where it is important to carry information through a section or onto another section. This attribute is used in many of the following sections. Any field with a size of zero is rejected. Once this information has been linked, the fields are sent to the growing section.

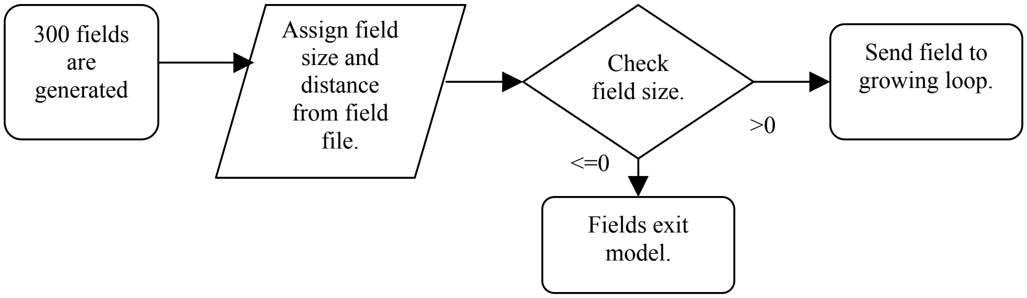


Figure 3.7 The field generation loop

3.6.3 Growing loop

The growing loop is shown in Figure 3.8. The growing section begins by reading the "cut" attribute of the field. This is used in later calculations to determine if the field is ready for growth. It is also used to eliminate fields that have already been cut the maximum number of times allowed by the operator. The field then passes to a decision block. This block checks the day and routes the field to either the growth queue or out of the system. This allows the operators to stop cutting after a specified date in order to allow a crop to grow adequately prior to snowfall. The field waits in the growth queue until the accumulated growth reaches the level specified in the information collection section. At that point, the field is passed from the growing loop into the mowing loop. The growth calculation is a standard for calculating the growth of various plants. It is based upon Equation 2.4 and shown in the delay calculation section of Appendix 4. The growth is based on the accumulation of heat units over the course of the year.

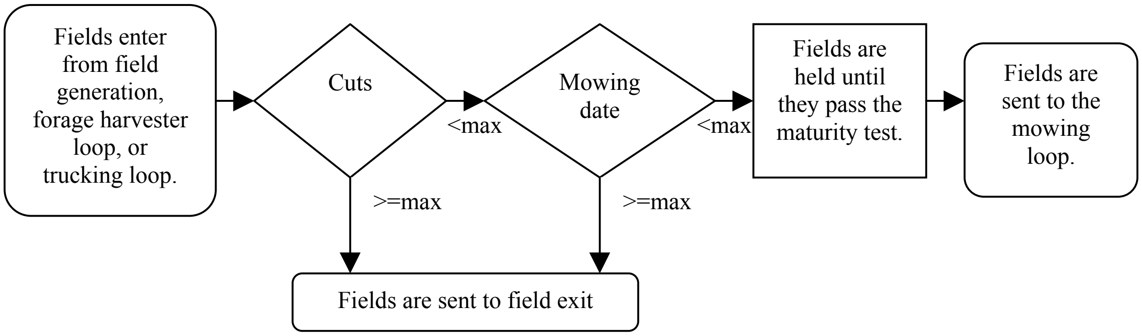


Figure 3.8 The growing loop.

3.6.4 Mowing loop

Figure 3.9 shows the mowing loop. The mowing loop catches the fields sent from the growing loop. The fields enter a decision block that checks the number of mowers in the system. If there are no mowers in the system, the field is determined to have been custom harvested. If there are mowers in the system, the field moves on to the next decision block. In this block, the maximum distance that the mowers can travel is compared to the distance from the facility to the field. If the field is beyond the maximum travel distance, the field is custom harvested. If the field is within the catchment area, the field is sent to the resource queue where it is held until there is a mower and a person available for it to continue. When a person and a mower are available, the field is sent to a decision block. This decision block checks the rainfall amounts and determines if it is too wet to work. If there is too much moisture, the mower and the person are released and the field waits for a day before the priority of the field is set to high and it is sent back to the beginning of the mowing loop. If it is dry enough to work, the field size and distance are read and the mower delay is calculated.

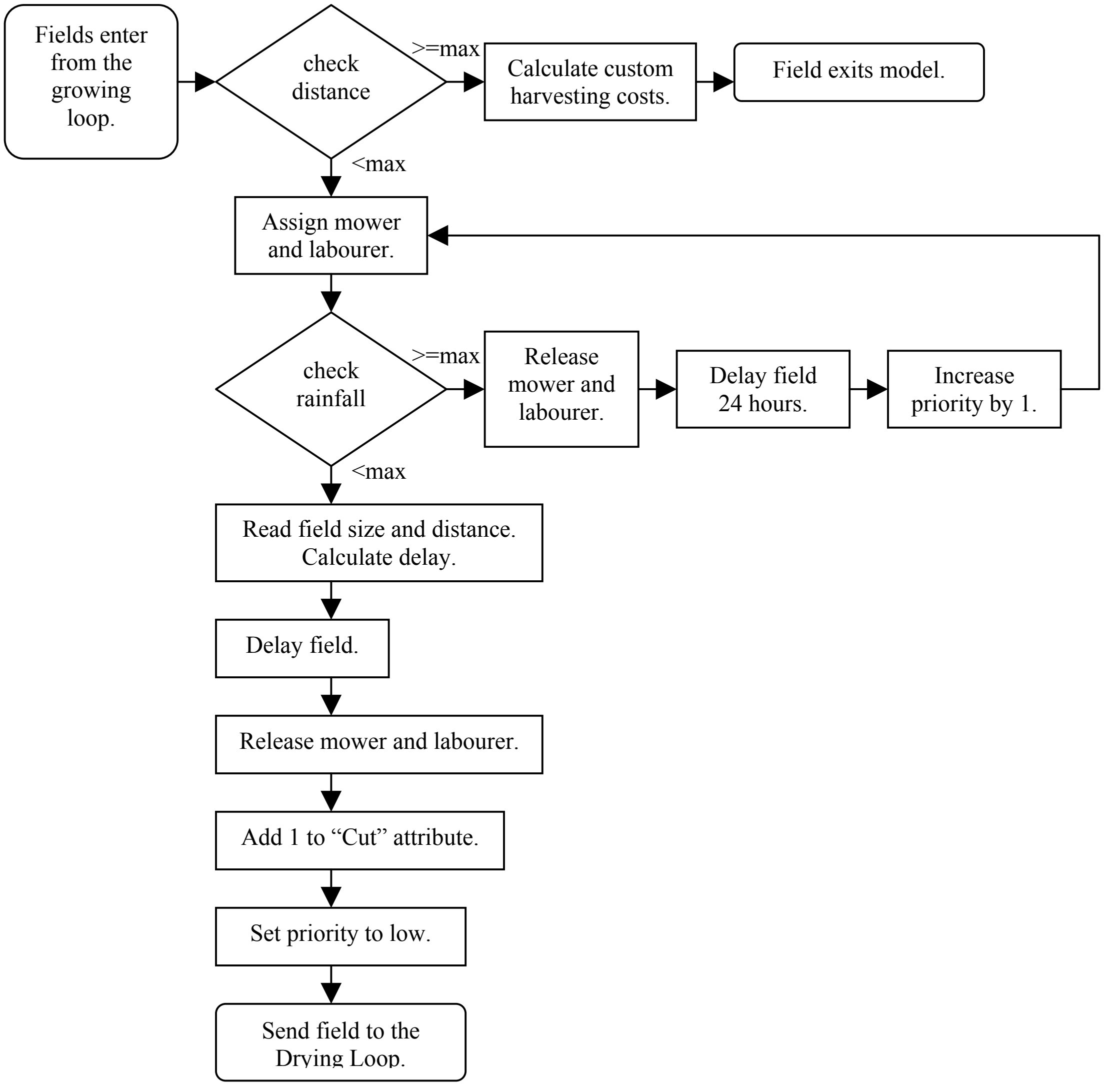


Figure 3.9 The mowing loop.

The mower delay calculation includes driving the mower to the field, mowing the field, and driving the mower back to the facility. These processes are combined to form the equation

$$\text{Delay} = \frac{\left(\frac{\text{FD}}{\text{RS}} * 2\right) + \left(\frac{\text{FS}}{\text{EC}}\right)}{\text{H}} \qquad \textbf{(3.4)}$$

where:

Delay = amount of time the equipment is used and the field is delayed (days),

EC = equipment capacity (ha/h),

FD = distance from facility to field (km),

FS = size of field (ha),

H = average working hours in a day (h/day), and

RS = road speed of equipment (km/h).

Once the mower delay is calculated, the field is held in the activity block for the duration required for cutting the field. When the time is up, the mower is released and passes through two “release resource” blocks that return the mower and the person to their “resource pools”. The “cut” attribute is then incremented by one, the priority is lowered, and the field is sent on to the drying loop.

3.6.5 Drying loop

The drying loop is actually two loops put together. Drying Loop 1 is shown in Figure 3.10. Drying Loop 2 is shown in Figure 3.11. The drying loops cycle the fields until they have dried for the number of days specified by the operator. The first loop and second loop are very similar. When the field enters the first drying loop, the “cycle use” attribute is read. In the drying loops, “cycle use” is used to keep a tally of the number of dry days that the field has gone through. If the field has dried for less then a day (“cycle use” is less then one), the field is passed to the next decision block. This decision block checks for rain. If there is rain, the field passes to another decision block that checks the amount of rain. If there is a lot of rain (as defined by the operator in the information section) the “cycle use” value is decreased by one, and the field is held for a day before being returned to the beginning of the loop. If there is enough rain to stop work, but not to set back the drying (0 ≤ rainfall ≤ sets back drying), the "cycle use" attribute is not adjusted and the field is sent back to the beginning of the drying loop after being delayed for a day. If there is no rain, the field is delayed for a day, the "cycle use" attribute is incremented by one, and then the field is returned to the beginning of the drying loop. In this first drying loop, the field continues until it has dried for one complete day ("cycle use" attribute is equal to one). When this happens, the field is sent to the forage harvester loop.

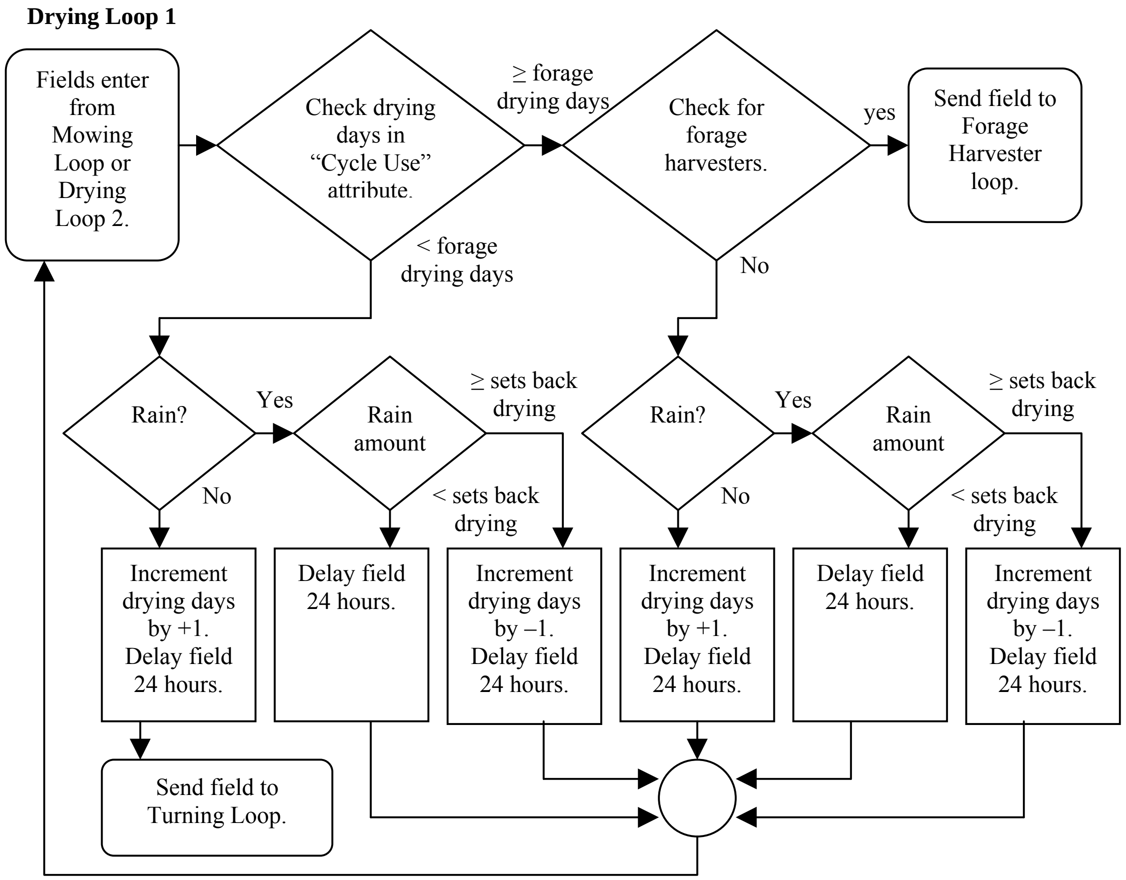


Figure 3.10 Drying Loop 1.

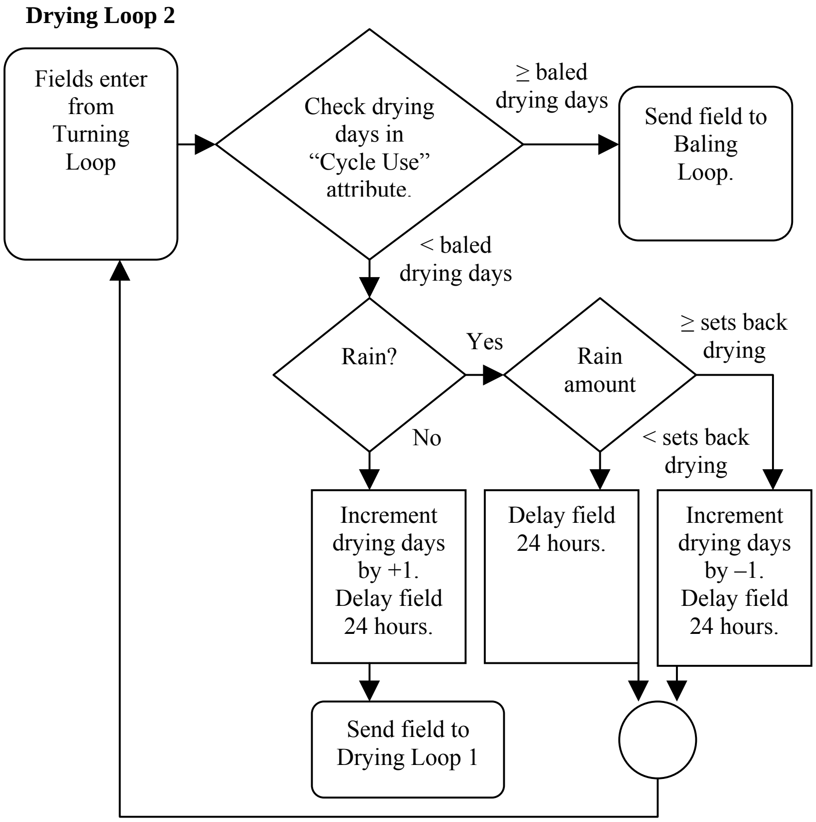


Figure 3.11 Drying Loop 2.

The second drying loop is similar to the first, however, it continues to loop the fields until they are dry enough to bale. After each dry day, the field is sent on to the turning loop. If turners are used, the field requires 4 dry days before being passed on to the baling loop. If turners are not being used, the fields are required to dry for 5 days. The duration that the field dries can be adjusted according to the normal or historical conditions of the area that the facility is located.

3.6.6 Turning loop

The turning loop is shown in Figure 3.12. Not all forage operations use turners to decrease drying time. As a result, the first decision block in the turning loop checks to see if any turners have been input in the information section. If there are no turners in use, the field is sent directly to the beginning of the "Drying 2" loop. If turners are used, then the field enters the resource pool queue. The field waits in the queue until there is a turner and a person available for the work. Once those requirements have been met, the field continues through blocks that read the size of the field and the distance from the facility. These are used to calculate the turner delay that includes moving the turners to and from the field and the in-field operations.

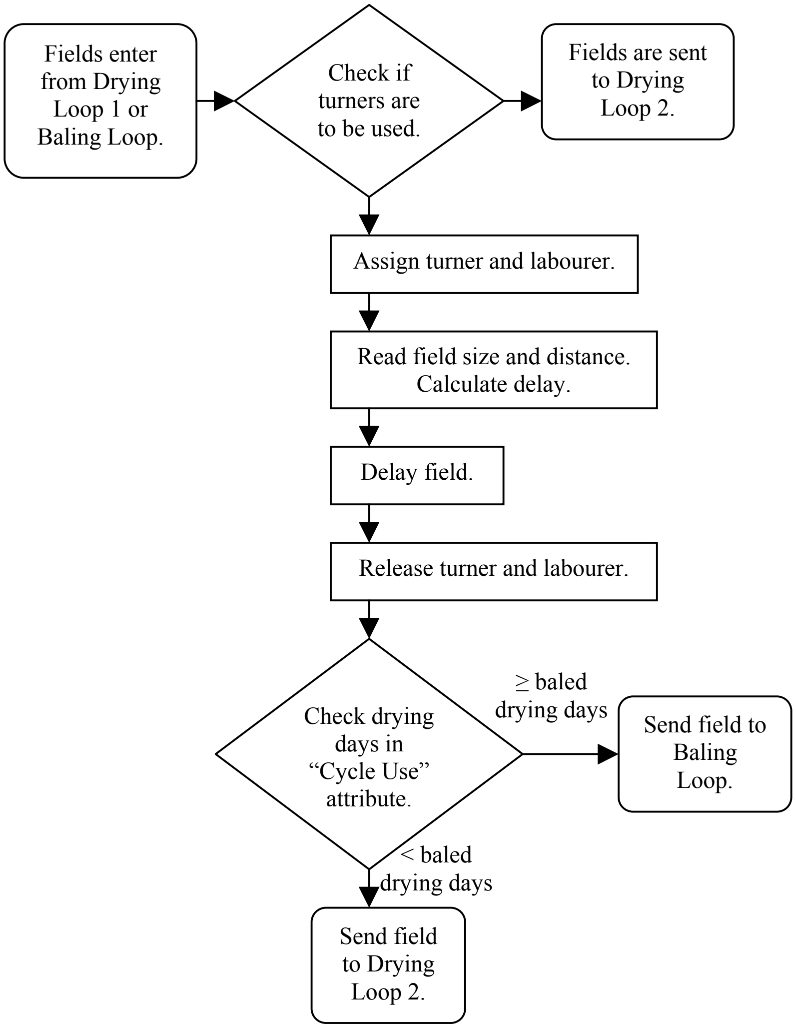


Figure 3.12 The turning loop.

The turning delay calculation is the same as Equation 3.1, using the turning speed and capacity instead of the mower capacity. The field then passes into the activity delay where it is held for the appropriate amount of time. When that time has passed, the field passes through the "release resource" blocks and the person and mower are returned to their respective resource pools. The field is then passed back to the "Drying 2" loop.

3.6.7 Forage harvester loop

The forage harvester loop is shown in Figure 3.13. The first decision in this loop determines whether or not there are any forage harvesters available for use. If there are none (because they are all assigned or there are none used in this system), the field is sent to the turning loop, where it can continue to dry and then be baled. If there is a forage harvester available, the field is sent to the next decision block. In this decision block, the distance of the field is compared to the maximum distance that the forage harvesters can travel. If the field is further away, the field is sent back to the drying loop to be baled. If the field is within the travel area, the field is sent to the first resource queue. In this queue, a mower, person, and wagon are assigned to the field. The field passes to a second queue where a truck, another person, and another wagon are assigned. This allows the forage harvester to be operated in field (with a wagon being pulled behind) while a second wagon is being taken to the facility and unloaded. The maximum time required for these two different operations is used to delay the field before it continues to the next part of the loop. The delay is calculated by

$$\text{Delay} = \text{MAX}\begin{bmatrix} \dfrac{\text{FS}}{\text{EC}_{\text{FH}}\times} + \dfrac{2\times\text{FD}}{\text{RS}_{\text{FH}}} \\ \dfrac{\text{FS}\times\text{Y}}{\text{EC}_{\text{W}}\times\text{EN}_{\text{W}}}\times\left(\dfrac{2\times\text{FD}}{\text{RS}_{\text{W}}}+\text{WU}\right) \end{bmatrix} \div \text{H}\ , \qquad \textbf{(3.5)}$$

where:

EC = equipment capacity (ha/h for most equipment, t for wagons)

EN = number of pieces of equipment,

FD = distance from facility to field (km),

$_{\text{FH}}$ = forage harvester,

FS = size of field (ha),

H = average working hours in a day (h/day),

MAX = the maximum value of the two options presented,

RS = road speed of equipment (km/h),

$_{\text{W}}$ = wagon,

WU = wagon unload time (h), and

Y = yield (kg/ha).

Once the delay has been met, the field passes through the appropriate release blocks, the “cycle use” attribute is set to zero, and the field is sent back to the growth loop.

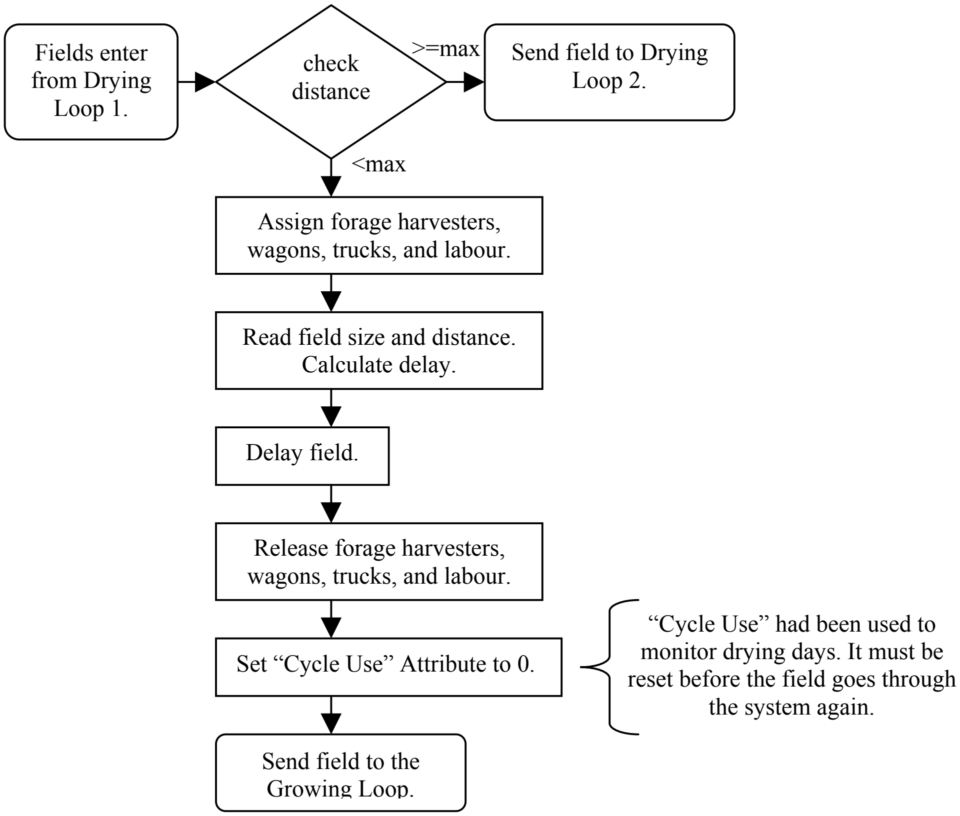


Figure 3.13 The forage harvester loop.

3.6.8 Baling loop

The baling loop is shown in Figure 3.14. The field is compared to the maximum travel distance and then is either custom baled or sent through the baling loop. The field then passes through a resource queue where a baler and a person are assigned to the field. The rainfall is then checked to determine if it is dry enough to work. If it is not, the resources are released, the field is delayed, prioritized, and sent back to the beginning of the baling queue. If it is dry enough to work, the size and distance are read, the baling delay is calculated (equation 3.1) and the field is appropriately delayed. The resources are then released. The number of bales produced is calculated and stored in the "cycle use" attribute to be used in the trucking loop.

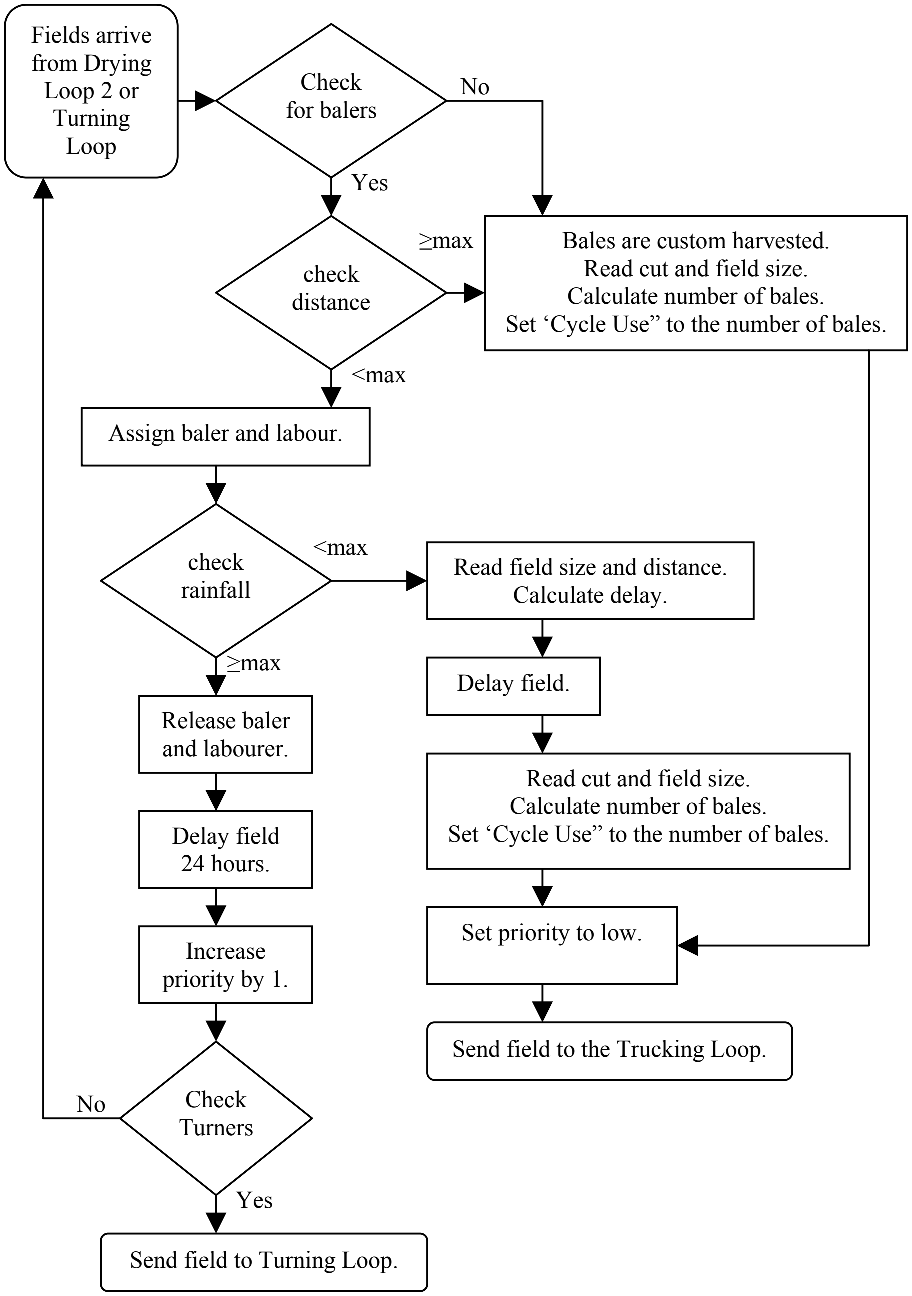


Figure 3.14 The baling loop.

3.6.9 Trucking loop

The trucking loop is shown in Figure 3.15. The first step in the trucking loop is to determine if the field is to be custom trucked or if trucking is done in-house. Custom trucking includes custom loading on the field and in-house loading at the facility. Custom trucking is assumed for fields beyond an input maximum distance. The in-house section of the trucking loop begins by checking the rainfall. If it is too wet, the fields are delayed by a day, prioritized and returned to the beginning of the baling queue. If it is dry, then the field is assigned a truck, flatbed, lifter, and two people. The distance is read and the time required to transport the equipment is calculated by,

$$\text{Delay} = \text{MAX}\begin{bmatrix} \dfrac{2 \times \text{FD}}{\text{RS}_\text{L}} \\ \dfrac{2 \times \text{FD}}{\text{RS}_\text{T}} \end{bmatrix} \div \text{H}, \qquad \textbf{(3.6)}$$

where:

Delay = amount of time the equipment is used and the field is delayed (days),

FD = distance from facility to field (km),

FD = distance from facility to field (km),

H = average working hours in a day (h/day),

$_\text{L}$ = lifter,

MAX = the maximum value of the two options presented,

RS = road speed of equipment (km/h), and

$_\text{T}$ = truck

The field is delayed the appropriate amount of time and then one of the people is released. A single person uses the lifter to load the flatbed and then transports the flatbed of bales to the main facility. The size, distance, and “cycle use” (number of bales) attributes are read and the field is again delayed;

$$\text{Delay} = \left(\sqrt{\frac{\text{FS} \times 0.04}{\pi}} \times \frac{2 \times \text{B}}{\text{FS}_\text{L}}\right) + \left(\text{B} \times \text{LT}\right) + \left(\frac{\text{B}}{\text{BT}} \times \left(\frac{2 \times \text{FD}}{\text{RS}_\text{T}} + \text{UT}\right)\right) \div \text{H}, \textbf{(3.7)}$$

where:

B = number of bales in a field,

BT = number of bales per truck load,

Delay = amount of time the equipment is used and the field is delayed (days),

FD = distance from facility to field (km),

FS = size of field (ha),

H = average working hours in a day (h/day),

$_{L}$ = lifter,

LT = load time per bale (h),

RS = road speed of equipment (km/h),

$_{T}$ = truck, and

UT = unload time per truck (h).

The remaining resources are released, the field’s priority is again lowered, and the field is sent back to the growing loop.

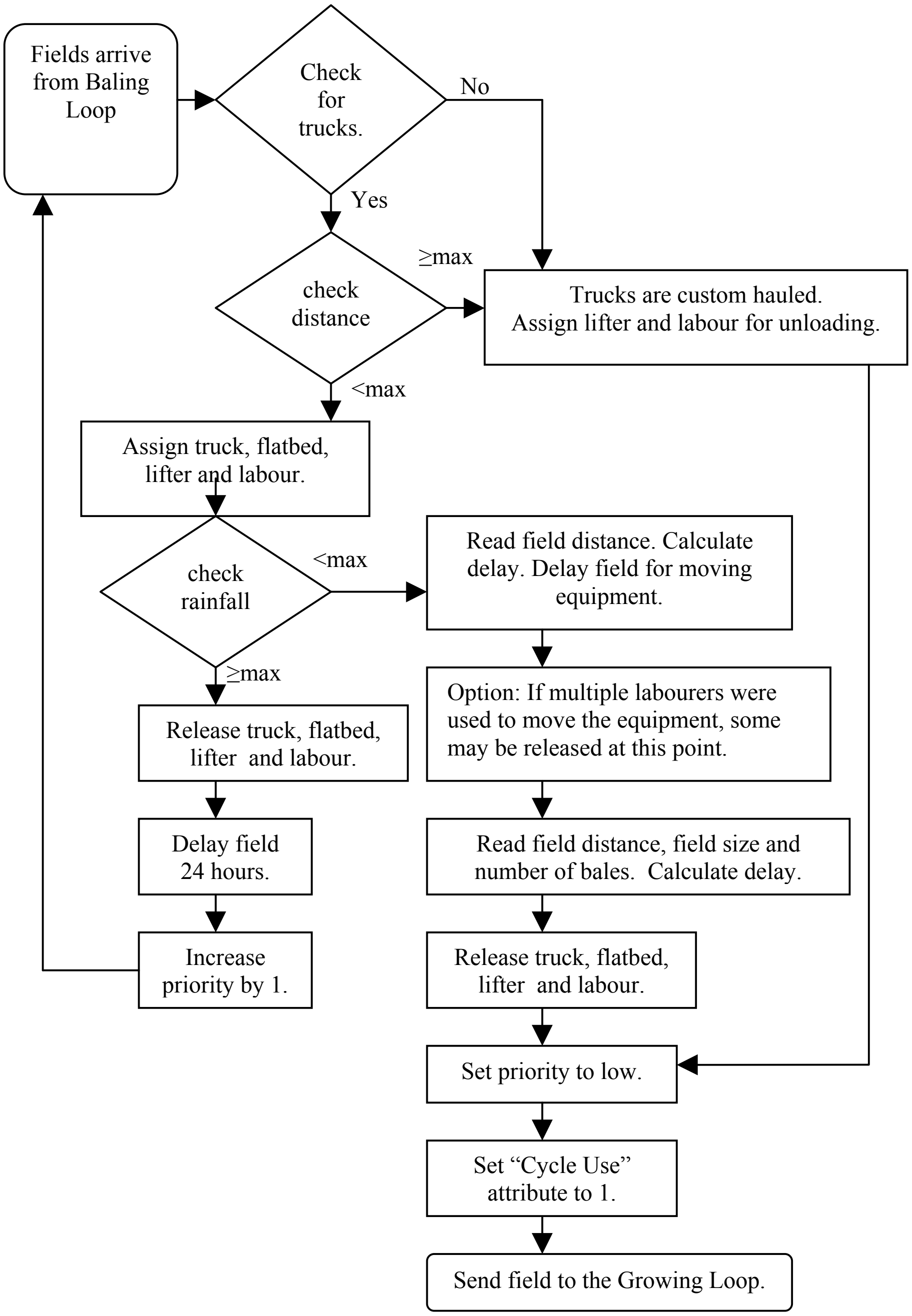


Figure 3.15 The trucking loop.

3.6.10 Field exit

The field exit is shown in Figure 3.16. This section is only accessible through the time out aspect of the growing loop. This allows the fields to leave the system so that the model can end with the year.

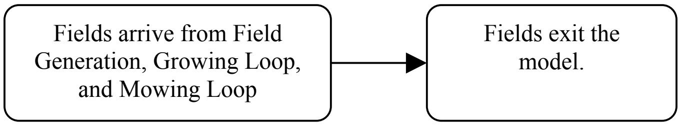


Figure 3.16 The field exit of the model.

3.6.11 Changing resource allocations

The resource allocations for each process can be changed to describe the operation for different facilities. For example, a facility may want to assign an extra person to the forage harvester operation to act as an overseer. Changing the resource allocation is done in the model itself. The operator goes to the loop where changes are to be made. The "queue, resource pool" block is opened and the number of resources allocated is adjusted. The corresponding "release resources" block must then be changed. These two blocks need to match. If there are more resources assigned than released, the program will stall when all of the resources have been allocated. If there are more resources released than assigned, the program will continue to add resources and the model will not be representative of the actual facility. These blocks are described in Appendix 5.

4. RESULTS AND DISCUSSION

This section deals with the validation of the model as well as three different scenarios that a manager might face. The scenarios were carried out using a simulated facility located near Outlook, Saskatchewan.

4.1 Validation

The validation was done by comparing the results of the model to the results of two different facilities. One facility works exclusively with baled alfalfa and timothy (Facility 1). The other facility deals primarily with wet forage and a few bales in the off season. (Facility 2). The field data, labour rates, hours of operation, equipment sizes, equipment numbers, and initial equipment costs were obtained for each facility. Information about how the resources are allocated was also collected. The repair and maintenance costs and the fuel costs were calculated in the worksheet section of the model. The yields were obtained from the Saskatchewan Crop Insurance Corporation (SCIC) as the average yield for the appropriate areas (Saskatchewan Crop Insurance Corporation, 2005). The facilities were modeled over 10 years of data and the results were compared with the actual costs for the facility.

Facility 1 is a sun-cured forage facility. They do their own mowing, turning and trucking for the fields that were analyzed. Baling is done by a custom harvester. Their costs are typically around $33/tonne of alfalfa (at baling moisture, approximately 13% w.b.). The costs generated for Facility 1 were 3 to 14% higher than the actual costs over the 10 years of data, with 8.5% being the average difference. The highest cost year was 1995, at

$37.65/tonne. The lowest cost year was 1996, at $34.20/tonne. In wet years, weather conditions require extra turning, while higher yields result in lower costs per tonne. The differences between the model and the actual costs were likely due to inconsistencies in the structure of the model as compared to an actual facility. For example, the travel time to and from the fields may be greater in the model than in reality, because the model assumes that the equipment always returns to the facility. The model sent each field through the mowing loop twice. Table 4.1 shows the modeled results for each year, the yields for the area (from SCIC), and the percentage difference from the typical costs for the facility.

Table 4.1 The year, yield, and modeled operating costs for Facility 1.

Year	Yield (kg/ha, 13% w.b.)	Operating Costs $/tonne (modelled)	% difference	
1994	2061	$35.39	+7.2%	
1995	1850	$37.65	+14.1%	MAX
1996	2240	$34.20	+3.6%	MIN
1997	2101	$35.11	+6.4%	
1998	2102	$35.10	+6.4%	
1999	2065	$35.36	+7.2%	
2000	1983	$35.98	+9.0%	
2001	1926	$36.44	+10.4%	
2002	1975	$35.99	+9.1%	
2003	1869	$36.94	+11.9%	

Note: Based on a predicted cost of $33/ton.

Facility 2 is the fresh forage facility. They operate six mowers, two forage harvesters and five trucks as a unit that moves from field to field. They also employ two people to oversee the operation and help when required. Facility 2 operates with an average cost of $38/tonne (at 0% moisture). The results for Facility 2 were 5 to 12% above the actual data, with 8.3% above being a typical year. Results ranged from a high of \$42.60/tonne (in 2001), to a low of \$39.85/tonne (in 1995). For the fresh forage model, the yield was directly related to the costs. 2001 was the year with the highest cost and the lowest yield for the area. 1995 was the year with the lowest costs and the highest yields for the area. It is important to note that not all of the fields were cut twice in this model. The simulation was unable to send all of the fields through the mowing loop in the time allotted. The differences are due to difference in the actual operation compared to the model. This facility also harvests a large number of fields so the timing constraints can become more pronounced. (refer to section 4.5 for a further discussion.) Table 4.2 shows the modeled results for each year, the yields for the area (from SCIC), and the percentage difference from the typical costs for the facility.

Table 4.2 The year, yield, and modeled operating costs for Facility 2.

Year	Yield (kg/ha, 0% w.b.)	Operating Costs \$/tonne (modelled)	% difference	
1994	2140	\$40.34	+6%	
1995	2217	\$39.85	+5%	MIN
1996	1896	\$41.69	+10%	
1997	1969	\$40.78	+7%	
1998	1917	\$41.44	+9%	
1999	1859	\$41.86	+10%	
2000	1838	\$41.87	+10%	
2001	1780	\$42.60	+12%	MAX
2002	2029	\$40.44	+6%	
2003	2009	\$40.85	+8%	

Note: Based on a predicted cost of \$38/tonne.

Due to the cutting inconsistencies with the fresh facility model, the simulated facility more closely approximates the sun-dried forage facility.

4.2 Simulated Facility

The simulated facility had a total of 7 fields located within a distance of 10 km from the main site. The field data were shown in Table 3.1 and the equipment data are shown in Table 4.3. It was assumed that the price of fuel was $0.534/l.

Table 4.3 The equipment data for the simulated facility.

Equipment	Mower	Turner	Forage Harvester	Baler	Lifter	Truck	Flatbed	Labour
Number	1	0	0	1	1	1	1	2
Capacity (ha/h)	3.4			4.68	15		34	
Road Speed (km/h)	30			30	30	50		
Fuel Use (l/h)	13.4			13.4	13.4	13.4		
Hourly R&M ($/h)	18			14	6	10		12
Maximum Distance (km)	100			100			100	
Bale Size (kg)				750				
Time to load a bale (min)					3			
Time to unload a truck (min)					30			
Average paid hours/day								12
Fixed costs/employee								0
Width (m)	4			4				
Initial Cost ($)	40 K			100K	32 K			
Life (h)	1000			1500	1250			

Note: R&M are the repair and maintenance costs.
For Labour the Hourly R&M are the wages.
For Lifter the Capacity is the in-field speed (km/h).
Shaded cells mean that the information is not associated with that piece of equipment.
For Flatbed the Capacity is the number of bales per load.
Fuel use is based on a max PTO power of 60 kW, and 100% load.

Figure 4.1 shows the yields and cost per bale for the simulated facility over 10 years, from 1994 to 2003.

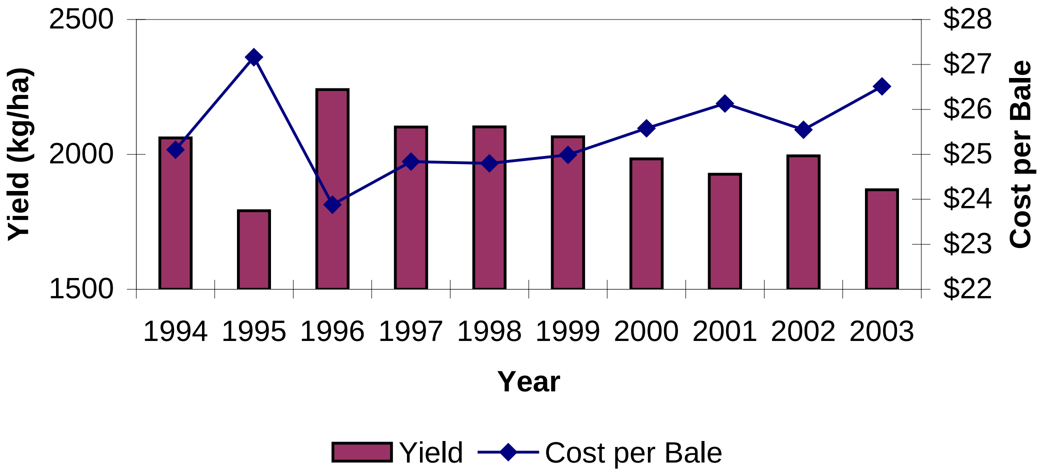


Figure 4.1 Yields and cost per bale for the simulated facility over ten years.

Table 4.4 shows one set of production costs of the simulated facility. These costs are for the year 2002, which was as close to the 10-year average of the facility as possible. It also shows the costs associated with fuel, labour, and repair and maintenance.

Table 4.4 The baseline production costs of the simulated facility, based on the 2002 weather data and yield.

	Mowing	Baling	Lifters	Tucking	Total	Total $/ton	Total $/bale	%
R&M	$5,226	$2,963	$1,603	$2,673	$12,465	$12.78	$9.58	40%
Fuel	$2,334	$1,702	$2,149	$2,148	$8,333	$8.54	$6.41	27%
Labour	$3,484	$240	$3,207	$3,207	$10,138	$10.39	$7.79	33%
Total	$11,044	$4,905	$6,959	$8,028	$30,936	$39.62	$23.78	
Total $/ton	$11.32	$5.03	$7.13	$8.23	$31.71			
Total $/Bale	$8.49	$3.77	$5.35	$6.17	$23.78			
%	36%	16%	22%	26%				

These costs are the baseline for the scenarios that were tested. Figure 4.2 shows how the fuel, labour, and repair and maintenance costs are broken down into mowing, baling, trucking, and lifters.

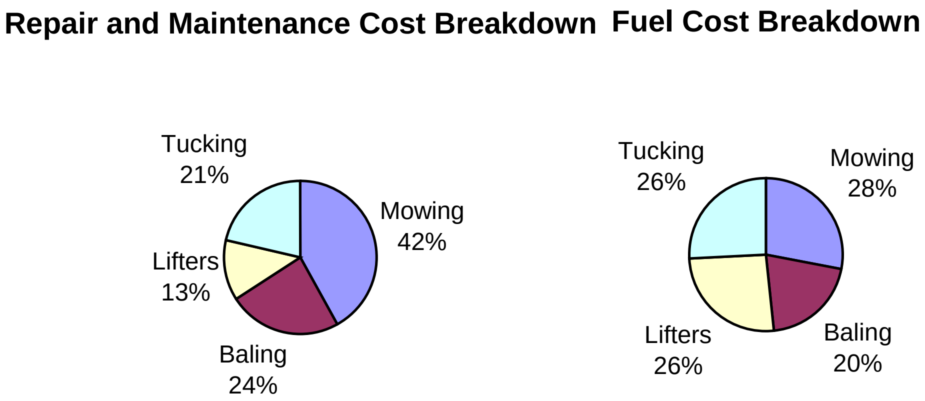
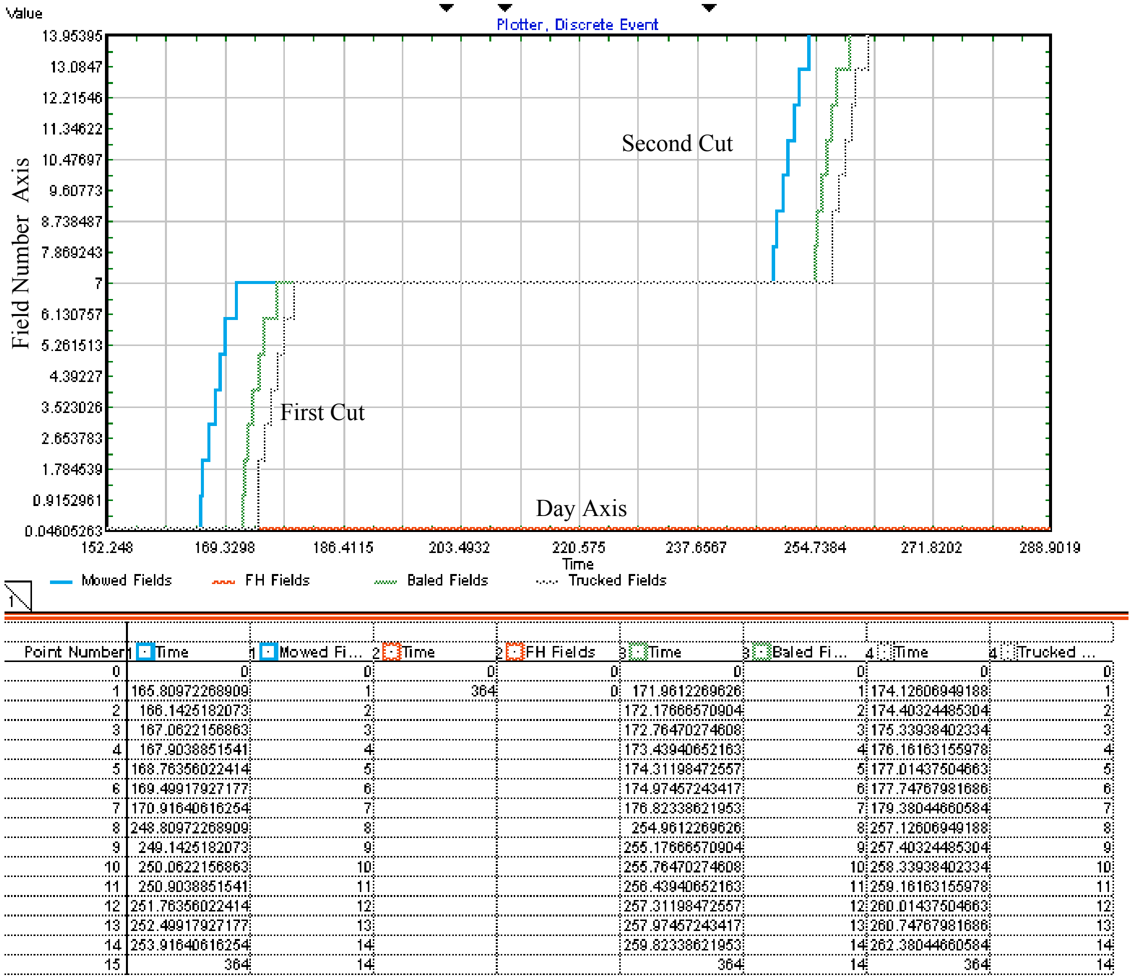


Figure 4.2 The percentage breakdown for labour and repair and maintenance costs, by process, for the simulated facility, based on the 2002 data.

The simulated facility cut each of the seven fields twice for a total harvest of 978 hectares. From this land base, 1312 bales, 750 kg each, were collected. The average yield was 2013 kg/ha.

The yields for 2002 were the closest to the average, therefore the 2002 data was used to evaluate the scenarios.

Figure 4.3 shows the date when each field finished each process. Fields 8-14 are the second cut of the first seven fields. The graph has been adjusted to focus on the days that there was work being done. The results correspond to the expected days or the first and second cuts of alfalfa in Saskatchewan. The first cut of alfalfa is usually mowed in the third week of June. (Sommerfeld, 2004)



Point Number	1 Time	1 Mowed Fi...	2 Time	2 FH Fields	3 Time	3 Baled Fi...	4 Time	4 Trucked ...
0	0	0	0	0	0	0	0	0
1	165.80972268909	1	364	0	171.9612269626	1	174.12606949188	1
2	166.1425182073	2			172.17666570904	2	174.40324485304	2
3	167.0622156863	3			172.76470274608	3	175.33938402334	3
4	167.9038851541	4			173.43940652163	4	176.16163155978	4
5	168.76356022414	5			174.31198472557	5	177.01437504663	5
6	169.49917927177	6			174.97457243417	6	177.74767981686	6
7	170.91640616254	7			176.82338621953	7	179.38044660584	7
8	248.80972268909	8			254.9612269626	8	257.12606949188	8
9	249.1425182073	9			255.17666570904	9	257.40324485304	9
10	250.0622156863	10			255.76470274608	10	258.33938402334	10
11	250.9038851541	11			256.43940652163	11	259.16163155978	11
12	251.76356022414	12			257.31198472557	12	260.01437504663	12
13	252.49917927177	13			257.97457243417	13	260.74767981686	13
14	253.91640616254	14			259.82338621953	14	262.38044660584	14
15	364	14			364	14	364	14

Figure 4.3 The field processing dates for simulated facility. The table and graph were generated by the model.

4.3 Sensitivity Analysis – Fuel Costs

The fuel costs are high in both sun-dried and fresh forage operations. Not only are there fuel costs associated with harvesting, but both facilities require fuel to dry the material during the cubing process. It is also important to note the fuel costs also impact the repair and maintenance costs with respect to oil and grease required for equipment upkeep. The model simulates the fuel costs with respect to the fuel used by the equipment only. The facilities' fuel costs are not incorporated and the repair and maintenance increase is shown in the workbook.

The simulated facility ran initially with a fuel cost of $0.60/L. At this rate, the fuel costs accounted for approximately 27% of the cost of producing a bale and a portion of the repair and maintenance costs for grease and oil. Table 4.5 shows the volume and costs of fuel associated with each process. Figure 4.4 shows the breakdown of the processes as a percentage of the fuel costs.

Table 4.5 Costs and volume of fuel associated with each process, modeled facility, 2002.

	Mowing	Baling	Lifters	Tucking
Total $	$2,334	$1,702	$2,014	$2,014
$/bale	$1.79	$1.31	$1.55	$1.55
Total L	3,890	2,837	3,357	3,357
L/bale	2.99	2.18	2.58	2.58

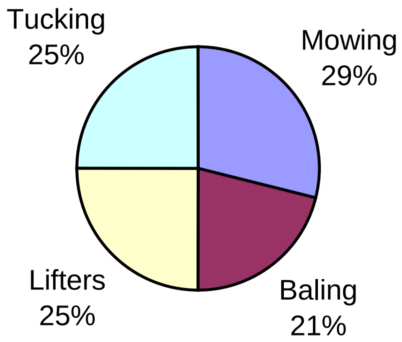


Figure 4.4 Process breakdown of the fuel cost, modeled facility, 2002.

Table 4.6 shows the fuel costs at four different levels and the increase in the percentage of the total costs associated with fuel. Figure 4.5 shows the difference between the extremes of $0.60/L and $2/L.

Table 4.6 The effects of increasing fuel costs, simulated facility, 2002.

Price ($/l)	$0.60	$1.00	$1.50	$2.00
Fuel	$8,064	$13,891	$20,836	$27,781
Total	$32,967	$38,796	$45,741	$52,686
Total ($/bale)	$25.34	$29.82	$35.16	$40.50
Fuel (% of total cost)	24%	36%	46%	53%

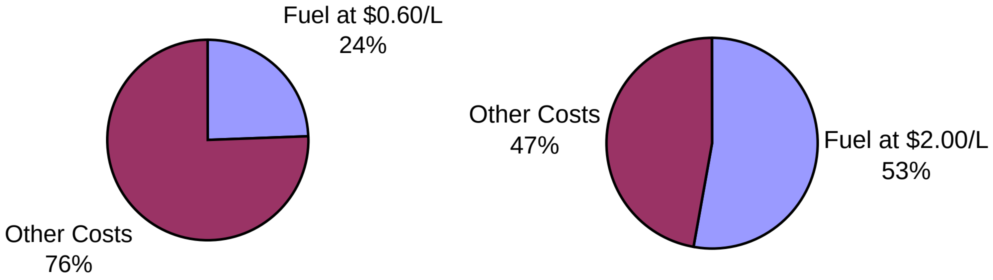


Figure 4.5 The change in fuel costs as a percentage of the total operational costs for the simulated facility, 2002.

It is important to note that these facilities also require fuel for drying the material during processing at the facility. These changes in the fuel costs only begin to indicate how increasing fuel costs can affect alfalfa cubing facilities.

4.4 Sensitivity Analysis – Labour Changes

Labour is one of the other factors involved in a production facility. Like fuel, the cost of labour can have a dramatic impact on a facility's bottom line. However, unlike fuel, labour can also impact the amount of material that is collected in a given year.

Table 4.7 shows the effects of the cost of labour at \$9/h, \$12/h, \$15/h, and \$18/h. Figure 4.6 shows the difference in the extremes of \$9/h and \$18/h.

Table 4.7 The effects of changing labour costs on the operational costs of the simulated facility.

Price($/h)	$9.00	$12.00	$15.00	$18.00
Labour	$9,329	$12,438	$15,549	$18,659
Total	$29,858	$32,967	$36,078	$39,188
Labour (% Total Cost)	31%	38%	43%	48%

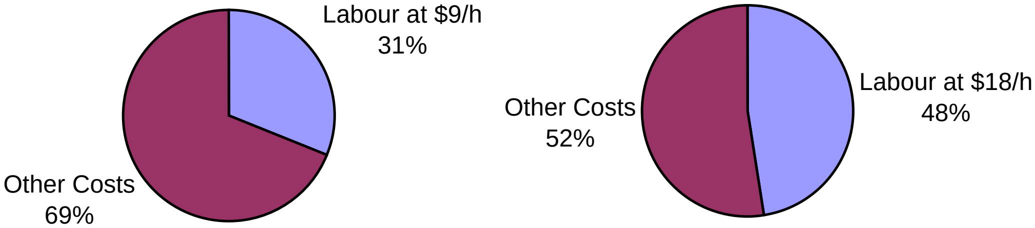


Figure 4.6 The effect of change in labour costs as a percentage of the total operational costs, simulated facility, 2002.

Using the same equipment, a single person would be able to harvest all of the material. However, as shown in Table 4.8, it would be later in the year when harvest for the single person was finished. Since all of the fields were harvested twice, an extra person would not increase the amount of material collected. This harvest is dependent upon the weather and crop growth more than the labour and equipment size. For this facility, the quality of the material would not be effected by reducing the labour requirements to a single person. However, if the labour shortage meant that the final bales were hauled after it snowed or if the mowing was delayed until late in the season, then the quality could be adversely affected.

Table 4.8 Harvest dates at the simulated facility with one, two, three and four people.

Cut	Field	Date Harvest Finished One Person	Two People	Three People	Four People
1	1	3-Jul	27-Jun	25-Jun	25-Jun
	2	4-Jul	27-Jun	26-Jun	26-Jun
	3	8-Jul	29-Jun	27-Jun	27-Jun
	4	9-Jul	30-Jun	28-Jun	28-Jun
	5	10-Jul	1-Jul	30-Jun	30-Jun
	6	11-Jul	2-Jul	1-Jul	1-Jul
	7	14-Jul	5-Jul	3-Jul	3-Jul
2	1	24-Sep	18-Sep	16-Sep	16-Sep
	2	25-Sep	18-Sep	17-Sep	17-Sep
	3	29-Sep	20-Sep	18-Sep	18-Sep
	4	30-Sep	21-Sep	19-Sep	19-Sep
	5	1-Oct	22-Sep	21-Sep	21-Sep
	6	2-Oct	23-Sep	22-Sep	22-Sep
	7	5-Oct	26-Sep	24-Sep	24-Sep

4.5 Sensitivity Analysis – Plant Capacity Increase

If management had the opportunity to add seven fields to their current production, how would it affect the amount of alfalfa able to be collected under the current operating system? Where would the delays be in the new system? What resources would be required in order for the facility to harvest these new fields?

When the facility increased their fields, the amount of time required to harvest the fields increased. However, there was still adequate time available for the collection of the bales from the first cut before the second cut of alfalfa was ready to harvest. After the second cut, it was getting late in the year when the last of the bales was brought into the facility. When the facility tripled the acreage, the bales from the second cut were brought to the facility just 16 days prior to snowfall.

It is also important to note that this facility is operating on 12-hour days. If they scale back to 8-hour days, then the final bales are being collected after it snowed on October 26th.

Figure 4.7 shows the harvest dates of 7, 14, and 21 fields working in 8 and 12 hour days. The dates are the days for the final transportation of the material from the field. The fields harvested prior to August 7th are the first cut. The fields harvested after August 7th are the second cut.

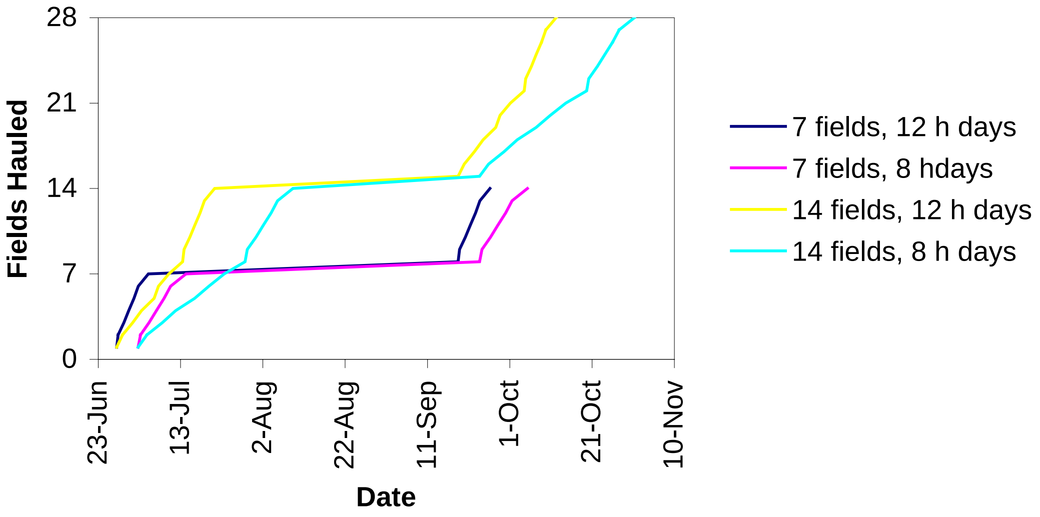


Figure 4.7 Projected dates for completing trucking for 7 and 14 fields with 8 and 12-hour days.

As the number of fields increase the delays switch from being related to crop growth and weather to being related to equipment size and labour availability.

4.6 Model Sensitivity

This model is very sensitive to both the capacities of the equipment and the repair and maintenance factors. The following sections explore those sensitivities.

4.6.1 Equipment capacity

The model is very sensitive to the capacities of the equipment, because the operating time of the equipment is calculated from the capacity. The capacities of the mowers and balers have a larger effect than the trucks or lifters in a sun-dried model.

The spreadsheet developed from the ASAE standards provides a range for the capacity of equipment. Table 4.9 shows the capacity ranges and the associated costs for a mower with a 4-m header.

Table 4.9 Mower operational costs modeled at three different capacities, for the simulated facility, 2002.

	Low Capacity 1.5 ha/h $/bale	Average Capacity 2.36 ha/h $/bale	High Capacity 3.4 ha/h $/bale
Mower Costs	$19.15	$12.20	$8.49
Other Equipment Costs	$17.24	$17.24	$17.24
Total	$36.39	$29.44	$25.73

The capacity of the mower can affect the costs associated with harvesting the material. Table 4.9 also shows why it is critical to balance the system based on the history of the facility that is being modeled. The capacity of the equipment can have a great impact on the costs.

4.6.2 Repair and Maintenance

The repair and maintenance costs tend to have the largest effect on the costs associated with operating equipment. Repair and maintenance costs can range from $6/h with lifters to $18/h with mowers. At $18/h the repair and maintenance costs make up approximately 47% of the total costs associated with mowing. (Table 4.10)

Table 4.10 Mowing cost breakdown for simulated facility, 2002.

	Mowers	%
Maintenance	$5,226	47%
Fuel	$2,334	21%
Labour	$3,484	32%
Total	$11,044	
$/bale	$8.49	

By reducing the cost of repair and maintenance by half to $9/h, the R&M costs associated with producing a bale drop by over $2/bale. (Table 4.11). This leads to the conclusion that when making new equipment purchases the repair and maintenance factor is more important then the fuel consumption of the equipment.

Table 4.11 Mowing cost breakdown for simulated facility, 2002, with reduced repair and maintenance costs.

	Mowers	%
Maintenance	$2,613	31%
Fuel	$2,334	28%
Labour	$3,484	41%
Total	$8,431	
$/bale	$6.48	

4.7 Results Summary

Th chapter explored various scenarios developed with the model. While it was found that the model will prove useful for management purposes, there were some limitations found through the sensitivity analysis. These limitations do not detract from the accuracy and utility of the simulation environment.

5. CONCLUSIONS

The objective of this thesis was to outline the development, verification and testing of a model that simulates the harvest and collection of forage from the field. The model was designed to be a managerial tool for the forage industry. A manager is able to balance the system, based on his/her facility history, and then run the simulation to determine how changes will affect the operation. The "what if" scenarios allow the manager to identify delays in their operations, as well as plan for upcoming years.

Balancing the system prior to making adjustments is critical in the operation of the model. Balancing involves adjusting the inputs so that the facility is accurately reflected in the model. This model can provide a reasonably accurate representation of forage collection providing that:

1. The operator adjusts the costs in the model to reflect their actual equipment, not necessarily the values that are provided through the spreadsheet. The ASAE standards from which the spreadsheet was developed reflect the operational costs of a variety of equipment over a fixed life span.

2. The operator chooses historical weather data and yields that are reflective of the type of conditions for which they are planning. There are differences based on the workability of the fields and the yields for each year.

The fuel costs are not dominated by any one type of equipment. The fuel costs account for approximately 24% of the total harvesting costs. Increasing the fuel costs can have very large consequences on the cost of the collection of materials. The modeled cost rose from \$25.34/bale to \$40.50/bale when the price of fuel rose from \$0.60/L to \$2.00/L.

The labour costs are not dominated by any one part of the process. However, the unloading and trucking processes combined require more labour then the other processes. An increase in the costs of labour by \$3/h results in a cost increase of \$2.39 per bale for the simulated facility.

The model can allow a manager to observe how changing the number of fields under production can affect the timing of harvest using the same equipment and people. It allows a manager to determine if he/she should increase the capacity of their equipment or increase the number of hours worked in a day to collect all of the material. The manager can also see what happens if he/she downsizes the facilities catchment area.

The model is more sensitive to high costs then to low costs. Maintenance-intensive equipment, such as mowers, tend to have their costs dominated by repair and maintenance.

The model also tends to be very sensitive to the field capacity of certain pieces of equipment. The lower the capacity is, the more sensitive the model is to the capacity. Low-capacity equipment tends to spend more time in the field, increasing the hours spent harvesting each tonne of forage.

REFERENCES

ASAE. 1999. Standard D497.4 - Agricultural Machinery Management Data. In *ASAE Standards*. 350-357. St Joseph, MI: American Society of Agricultural Engineers.

ASAE. 1999. Standard EP496.2 - Agricultural Machinery Management. In *ASAE Standards*. 344-349. St Joseph, MI: American Society of Agricultural Engineers.

Benock, G, O.J. Loewer, Jr., T. Bridges and D. H. Loewer. 1981. Grain flow restrictions in harvesting-delivery drying systems. *Transactions of the ASAE* 24(5):1151-1161.

Berggren, H. 1993. Project Agro-Fibre: an investigation of the possibility for using agricultural crops for pulp production in Sweden. In *New Crops for Temperate Regions,* ed. K.R.M. Anthony, J. Meadley, and G. Röbbelen, 14. London, UK: Chapman and Hall.

Berruto, R. and D. E. Maier. 2001. Analyzing the receiving operation of different grain types in a single–pit country elevator. *Transactions of the ASAE* 44(3):631–638.

Berruto, R., D. Ess, D. E. Maier and F. Dooley. 2003. Network Simulation of Crop Harvesting and Delivery from Farm Field to Commercial Elevator. *Electronic Proceedings of the International Conference on Crop Harvesting and Processing*, 9-11 February 2003, Louisville, Kentucky USA. ed. G. R. Quick. ASAE Publication #701P1103e. Online: www.asae.org

Environment Canada. 2005. Online: www.weatheroffice.ec.gc.ca.

Gilbert, N. and K. Troitzsch. 2002. *Simulation as a Method.* Simulation for the Social Scientist. Open University Press, Philadelphia

Gorzell, K.E. 2001. Finding an Economic and Environmental Balance to the Technology of Producing Building Materials from Agricultural Crop Residue. Paper No. 01-6075. St Joseph, MI: American Society of Agricultural Engineers.

Hansen, A.C., A.J. Barnes and P.W.L. Lyne. 2002. Simulation modeling of sugarcane harvest-to-mill delivery systems. *Transactions of the ASAE* 45(3):531-538.

Hunt, D.R. 1986. *Engineering Models for Agricultural Production.* AVI Publishing Co.

Imagine That Inc. 2005. San Jose, CA. Online: www.imaginethatinc.com

Jenkins, B.M., J.F. Arthur, P.A. Eibeck. 1983. Selecting Optimum Biomass Utilization Sites. *Transactions of the ASAE* 26(4) 1551-1556

Jenkins, B.M., R. Bakker-Dhaliwal, M.D. Summers, L.G. Bernheim, H. Lee, W. Huisman, and L. Yan. 2000. Equipment Performance, Costs and Constraints in the Commercial Harvesting of Rice Straw for Industrial Applications. Paper No. 006035. ASAE, 2950 Niles Rd., St Joseph, MI 49085-9659 USA.

Khoshtaghaza, M.H., S. Sokhansanj, B. Gossen, R.T. Patil, D.A. Pulkinen 1995. Quality of Alfalfa Cube During Storage. Paper No. 0956632. St Joseph, MI: American Society of Agricultural Engineers.

Klassen, G.D. 1994. Alternate Straw Use. Paper No. MBSK94-305. St Joseph, MI: American Society of Agricultural Engineers.

Krahl, D. 2001. The EXTEND simulation environment. *Proceedings of the 2001 winter Simulation Conference*. ed. E. Yücesan, C.H. Chen, J.L. Snowden, and J.M. Charnes, 217-225.

Meinardus, A., R.H. Griggs, V. Benson, and J. Williams. 1998. EPIC. Online: www.brc.tamus.edu/epic/

Microsoft Corporation. 2004. Redmond, WA. Online: www.microsoft.com

Nilsson, D. 1999. SHAM – a simulation model for designing straw fuel delivery systems. Part 1: model description. *Biomass and Bioenergy* 16 (1999) 25-38.

Nilsson, D. 1999. SHAM – a simulation model for designing straw fuel delivery systems. Part 2: model applications. *Biomass and Bioenergy* 16 (1999) 39-50.

Nilsson, D. 2000. Dynamic Simulation of Straw Harvesting Systems: Influence of Climatic, Geographical and Biological Factors on Performance and Costs. *J. Agric. Engng Res.* 76 (2000) 27-36.

Nilsson, D., Hansson, P.A. 2001. Influence of various machinery combinations, fuel proportions and storage capacities on costs for co-handling of straw and reed canary grass to district heating plants. *Biomass and Bioenergy* 20 (2001) 247-260.

Patil, R.T., S. Sokhansanj, E.A. Arinze, G.J. Schoenau. 1993. Methods of Expediting Drying Rates of Chopped Alfalfa. *Transactions of the ASAE* 36(6): 1799-1803

Rotz, C.A. and Y. Chen. 1985. Alfalfa drying model for the field environment. *Transactions of the ASAE* 28(5): 1686-1691

Saskatchewan Agriculture and Food. 2001. Saskatchewan Forage Crop Production Guide.

Saskatchewan Agriculture and Food. 2001. Farm Facts, Marketing Hay.

Saskatchewan Agriculture, Food and Rural Revitalization 2004. Farm Machinery Custom and Rental Rate Guide.

Saskatchewan Crop Insurance Corporation. 2004. Personal Communication.

Saskatchewan Highways and Transportation. 2000. A Guide to Saskatchewan Weight and Dimension Regulations. Online: www.highways.gov.sk.ca,

Sokhansanj, Shahab, Hugh C. Wood, Helen J. Streeton, William J. Crerar. 2000. Survey of Equipment and Facilities for Processing of High Density Bales. Paper No. 001038. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA.

Sokhansanj, Shahab. 2000. Chapter 1. Harvesting. Unpublished.

Sokhansanj, Shahab. 2000. Chapter 2. Baling. Unpublished.

Sokhansanj, Shahab. 2000. Chapter 6. Densification. Unpublished.

Sommerfeld, Greg. 2004. Personal Communication

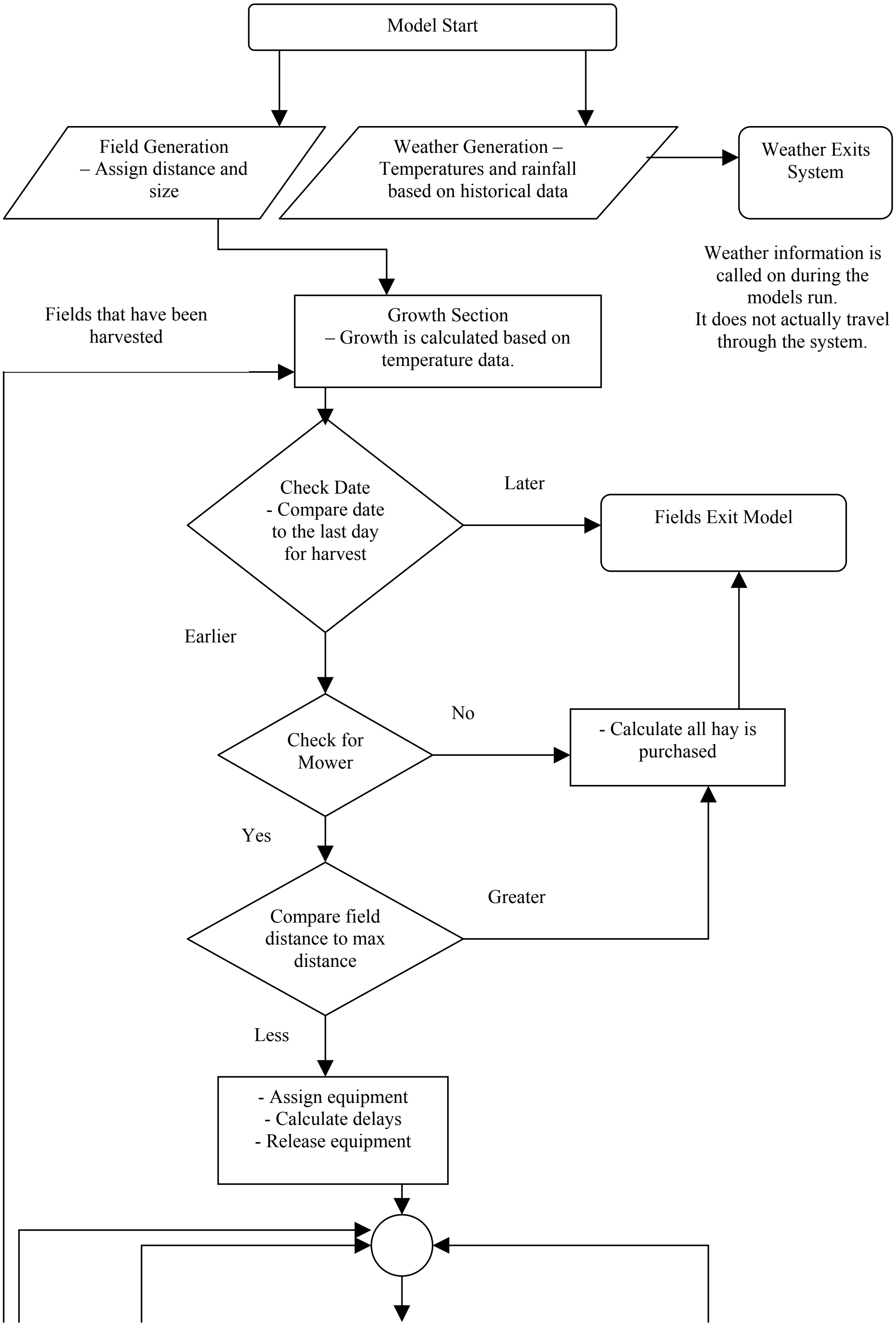
Sourie, J.C., and Rozakis, S. 2001. Bio-fuel production system in France: an Economic Analysis. *Biomass and Bioenergy* 20 (2001) 483-489

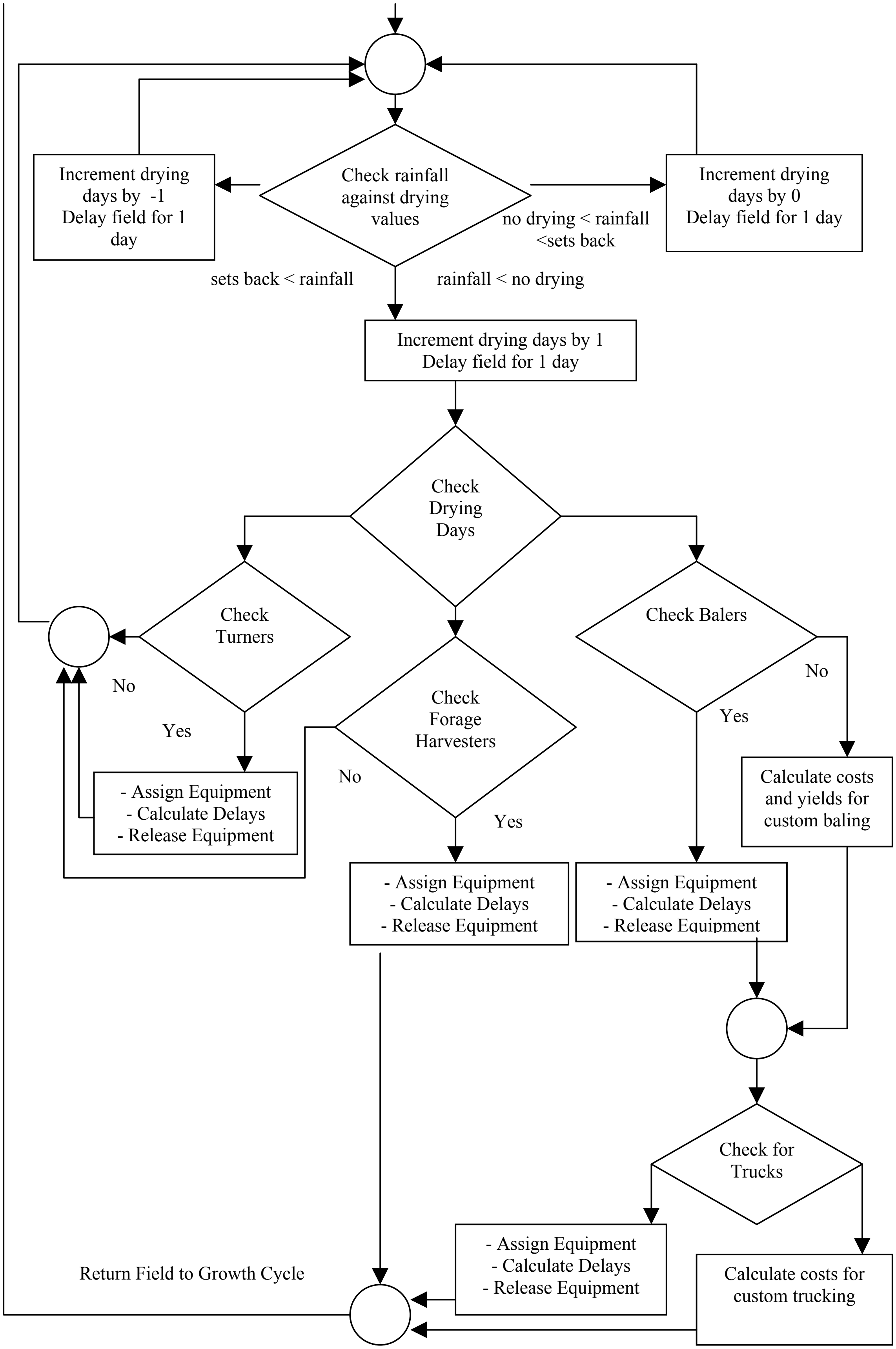
Tatsiopoulos, I.P. and A.J. Tolis. 2003. Economic aspects of the cotton-stalk biomass logistics and comparison of supply chain methods. *Biomass and Bioenergy* 24 (2003):199-214.

Turhollow, A., M. Downing, and J. Butler. 1998. *Forage Harvest and Transportation Costs.* Oak Ridge National Laboratory.

Turhollow, A.F. and S. Sokhansanj. 2004. Techno-economic assessment of transport and storage of corn stover in bulk. Paper No. 041165. St Joseph, MI: American Society of Agricultural Engineers.

APPENDIX 1 – MODEL FLOWCHART





Check rainfall against drying values
Increment drying days by -1 Delay field for 1 day
Increment drying days by 0 Delay field for 1 day
no drying < rainfall <sets back
sets back < rainfall
rainfall < no drying
Increment drying days by 1 Delay field for 1 day
Check Drying Days
Check Turners
Check Balers
No
Yes
Check Forage Harvesters
No
Yes
Calculate costs and yields for custom baling
- Assign Equipment
- Calculate Delays
- Release Equipment
Check for Trucks
Calculate costs for custom trucking
Return Field to Growth Cycle

APPENDIX 2 – SPREADSHEET

Equipment	Life	Width	Capacity		Price	Hourly R&M	Other Ownership Costs	Ave Diesel Use
			low	high			2%	l/h
	h	m	ha/h	ha/h			of total price	
Mower	1000	4	1.5	3.4	$40 K	$18	$800	13.36
Mower (rotary)	1000	4	2.4	6.84	$40 K	$18	$800	13.36
Rectangular baler	2000		0	0		$0	$0	0.00
Large rectangular baler	1500	4	1.82	4.68	$100 K	$14	$2,000	13.36
Large round baler	1500		0	0		$0	$0	0.00
Forage harvester	2500		0	0		$0	$0	0.00
Forage harvester (self propelled)	4000		0	0		$0	$0	0.00
Forage Wagon	2000					$0	$0	0.00
Wagon	3000					$0	$0	0.00
Windrower	3000	5	1.75	5.53	$4 K	$0.72	$80	13.36
Side Delivery Rake	1250	15	6.83	17.6	$32 K	$6	$640	13.36

Shaded cells indicate information that is input by the operator. Clear cells are calculated by the program.

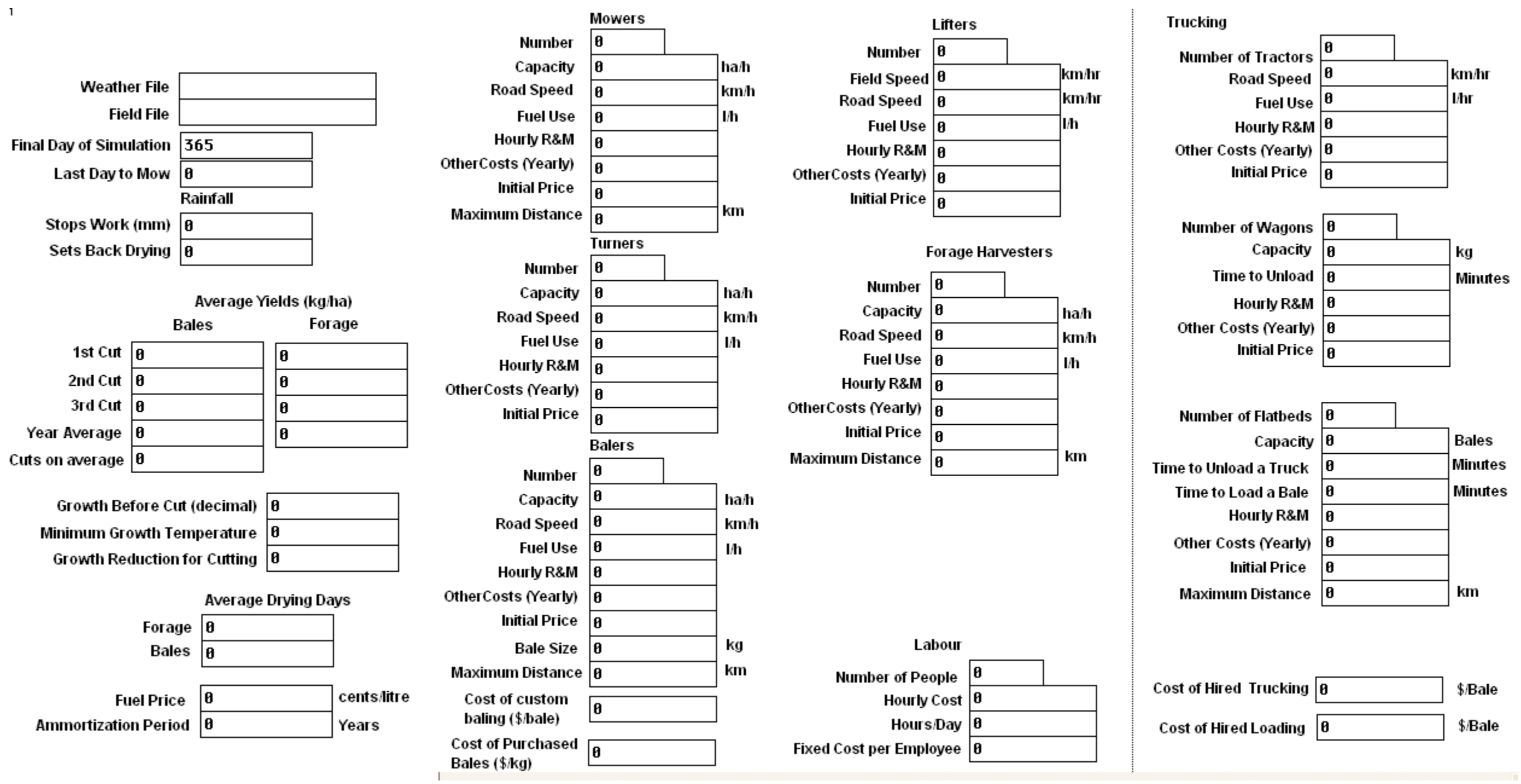
Adjust the life of the machine to reflect the typical life of equipment in your operation.

For Saskatchewan, the high capacity range is typical due to comparatively light yields.

Other Ownership Costs include taxes, housing and insurance.

APPENDIX 3 – USER INTERFACE

Inputs



Weather File
Field File
Final Day of Simulation 365
Last Day to Mow 0

Rainfall
Stops Work (mm) 0
Sets Back Drying 0

Average Yields (kg/ha)

	Bales	Forage
1st Cut	0	0
2nd Cut	0	0
3rd Cut	0	0
Year Average	0	0
Cuts on average	0	

Growth Before Cut (decimal) 0
Minimum Growth Temperature 0
Growth Reduction for Cutting 0

Average Drying Days
Forage 0
Bales 0

Fuel Price 0 cents/litre
Ammortization Period 0 Years

Mowers
Number 0
Capacity 0 ha/h
Road Speed 0 km/h
Fuel Use 0 l/h
Hourly R&M 0
OtherCosts (Yearly) 0
Initial Price 0
Maximum Distance 0 km

Turners
Number 0
Capacity 0 ha/h
Road Speed 0 km/h
Fuel Use 0 l/h
Hourly R&M 0
OtherCosts (Yearly) 0
Initial Price 0

Balers
Number 0
Capacity 0 ha/h
Road Speed 0 km/h
Fuel Use 0 l/h
Hourly R&M 0
OtherCosts (Yearly) 0
Initial Price 0
Bale Size 0 kg
Maximum Distance 0 km
Cost of custom baling ($/bale) 0
Cost of Purchased Bales ($/kg) 0

Lifters
Number 0
Field Speed 0 km/hr
Road Speed 0 km/hr
Fuel Use 0 l/h
Hourly R&M 0
OtherCosts (Yearly) 0
Initial Price 0

Forage Harvesters
Number 0
Capacity 0 ha/h
Road Speed 0 km/h
Fuel Use 0 l/h
Hourly R&M 0
OtherCosts (Yearly) 0
Initial Price 0
Maximum Distance 0 km

Labour
Number of People 0
Hourly Cost 0
Hours/Day 0
Fixed Cost per Employee 0

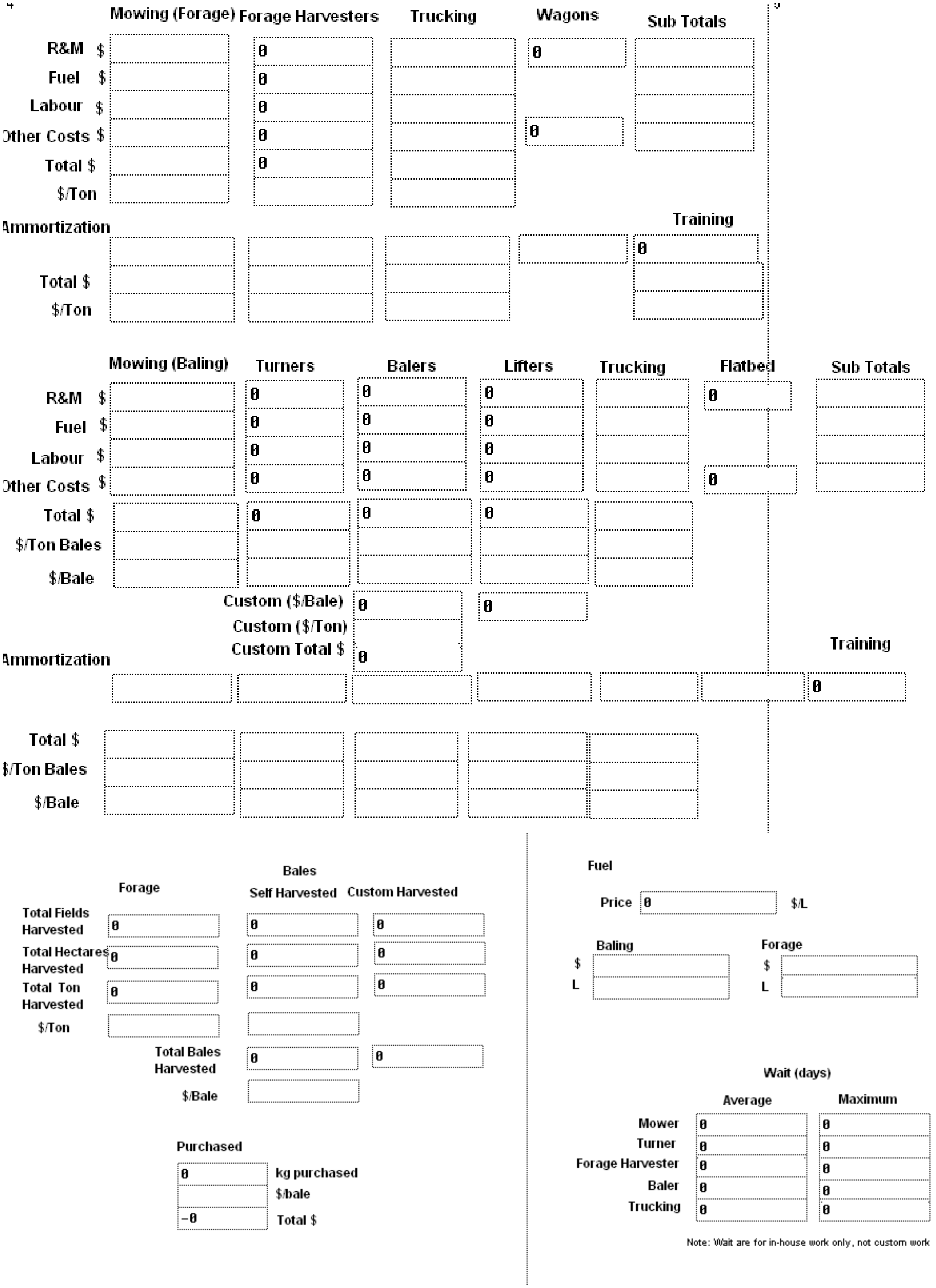
Trucking
Number of Tractors 0
Road Speed 0 km/hr
Fuel Use 0 l/hr
Hourly R&M 0
Other Costs (Yearly) 0
Initial Price 0

Number of Wagons 0
Capacity 0 kg
Time to Unload 0 Minutes
Hourly R&M 0
Other Costs (Yearly) 0
Initial Price 0

Number of Flatbeds 0
Capacity 0 Bales
Time to Unload a Truck 0 Minutes
Time to Load a Bale 0 Minutes
Hourly R&M 0
Other Costs (Yearly) 0
Initial Price 0
Maximum Distance 0 km

Cost of Hired Trucking 0 $/Bale
Cost of Hired Loading 0 $/Bale

Outputs



	Mowing (Forage)	Forage Harvesters	Trucking	Wagons	Sub Totals
R&M $		0		0	
Fuel $		0			
Labour $		0			
Other Costs $		0		0	
Total $		0			
$/Ton					

	Mowing (Forage)	Forage Harvesters	Trucking	Wagons	Training
Ammortization					0
Total $					
$/Ton					

	Mowing (Baling)	Turners	Balers	Lifters	Trucking	Flatbed	Sub Totals
R&M $		0	0	0		0	
Fuel $		0	0	0			
Labour $		0	0	0			
Other Costs $		0	0	0		0	
Total $		0	0	0			
$/Ton Bales							
$/Bale							
Custom ($/Bale)			0	0			
Custom ($/Ton)							
Custom Total $			0				

	Mowing (Baling)	Turners	Balers	Lifters	Trucking	Flatbed	Training
Ammortization							0
Total $							
$/Ton Bales							
$/Bale							

	Forage	Bales Self Harvested	Bales Custom Harvested
Total Fields Harvested	0	0	0
Total Hectares Harvested	0	0	0
Total Ton Harvested	0	0	0
$/Ton			
Total Bales Harvested		0	0
$/Bale			

Purchased

0	kg purchased
	$/bale
-0	Total $

Fuel

Price 0 $/L

	Baling	Forage
$		
L		

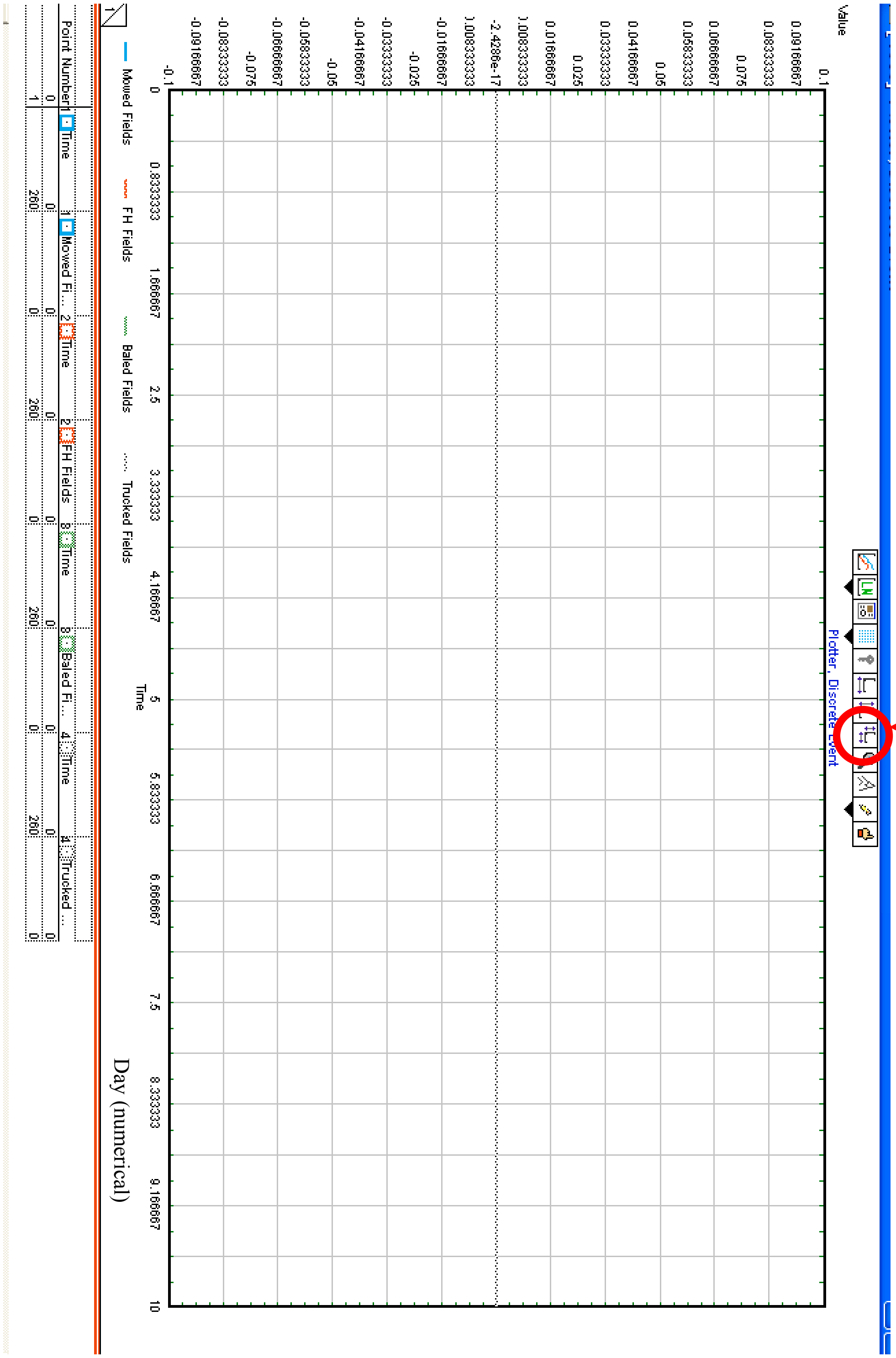
Wait (days)

	Average	Maximum
Mower	0	0
Turner	0	0
Forage Harvester	0	0
Baler	0	0
Trucking	0	0

Note: Wait are for in-house work only, not custom work

Graph

Field



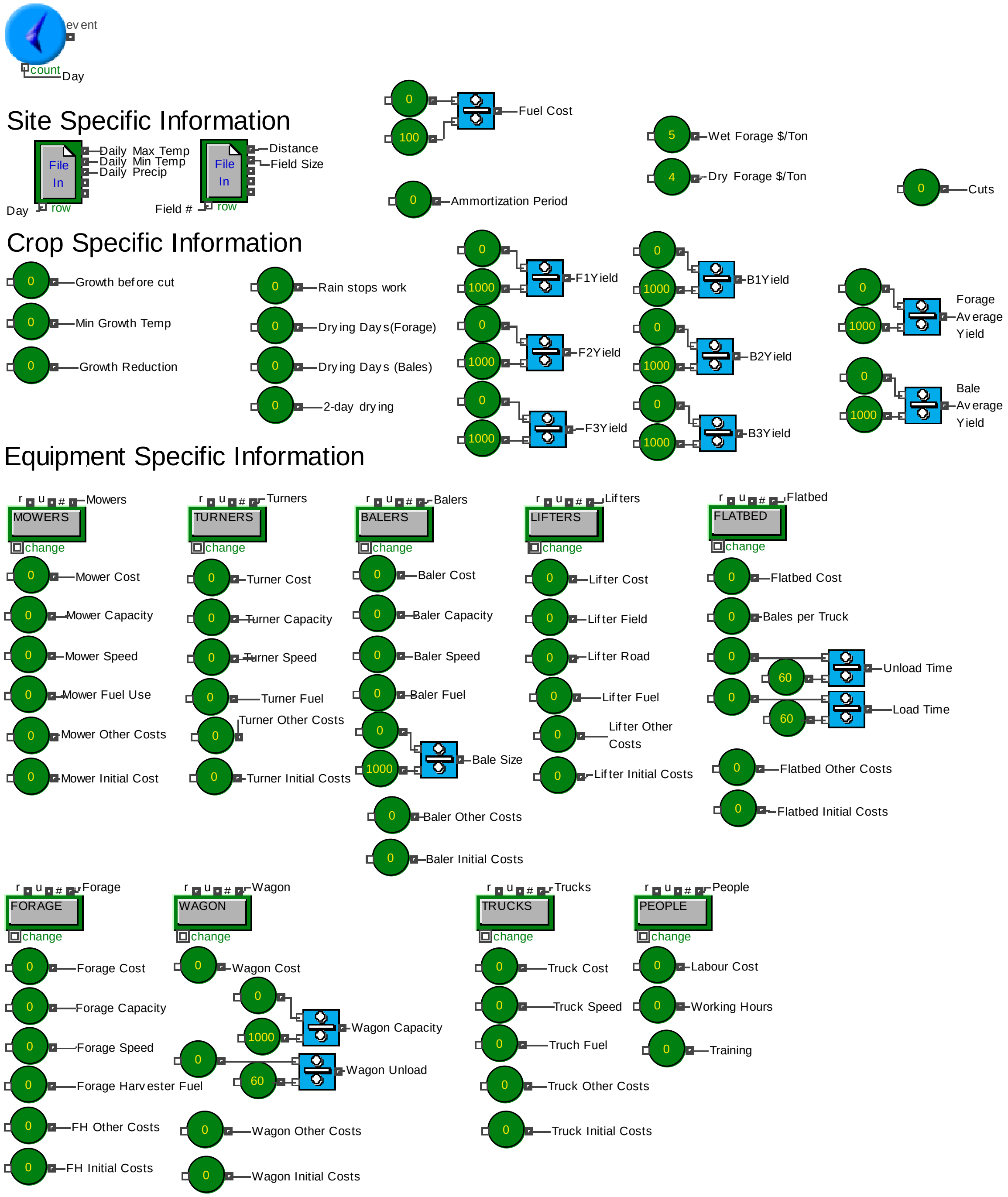
Point Number	Time	Mowed Fi...	Time	FH Fields	Time	Baled Fi...	Time	Trucked ...
0	0	0	0	0	0	0	0	0
1	260	0	260	0	260	0	260	0

Day (numerical)

This button changes the scale of the graph.

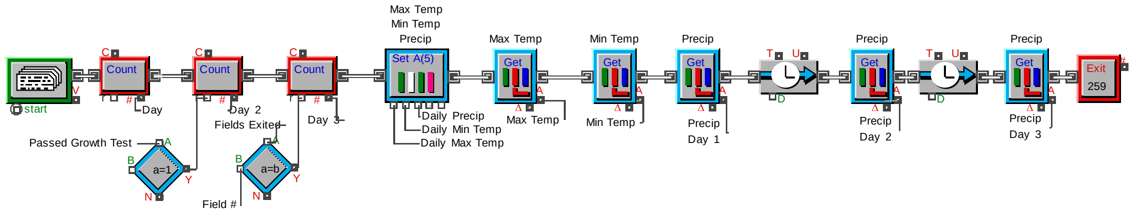
APPENDIX 4 – MODEL

Information Collection

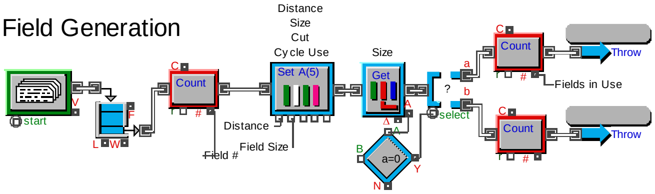


Field Movement

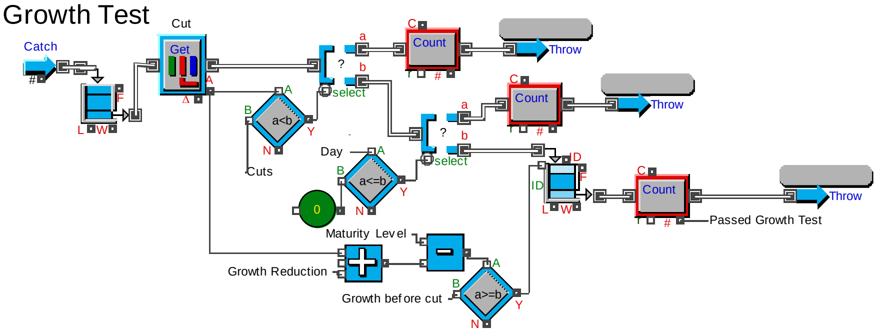
Weather Generation



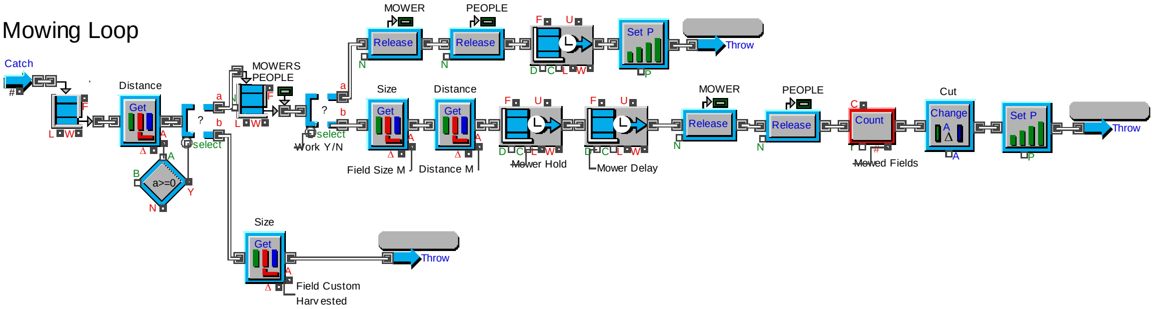
Field Generation



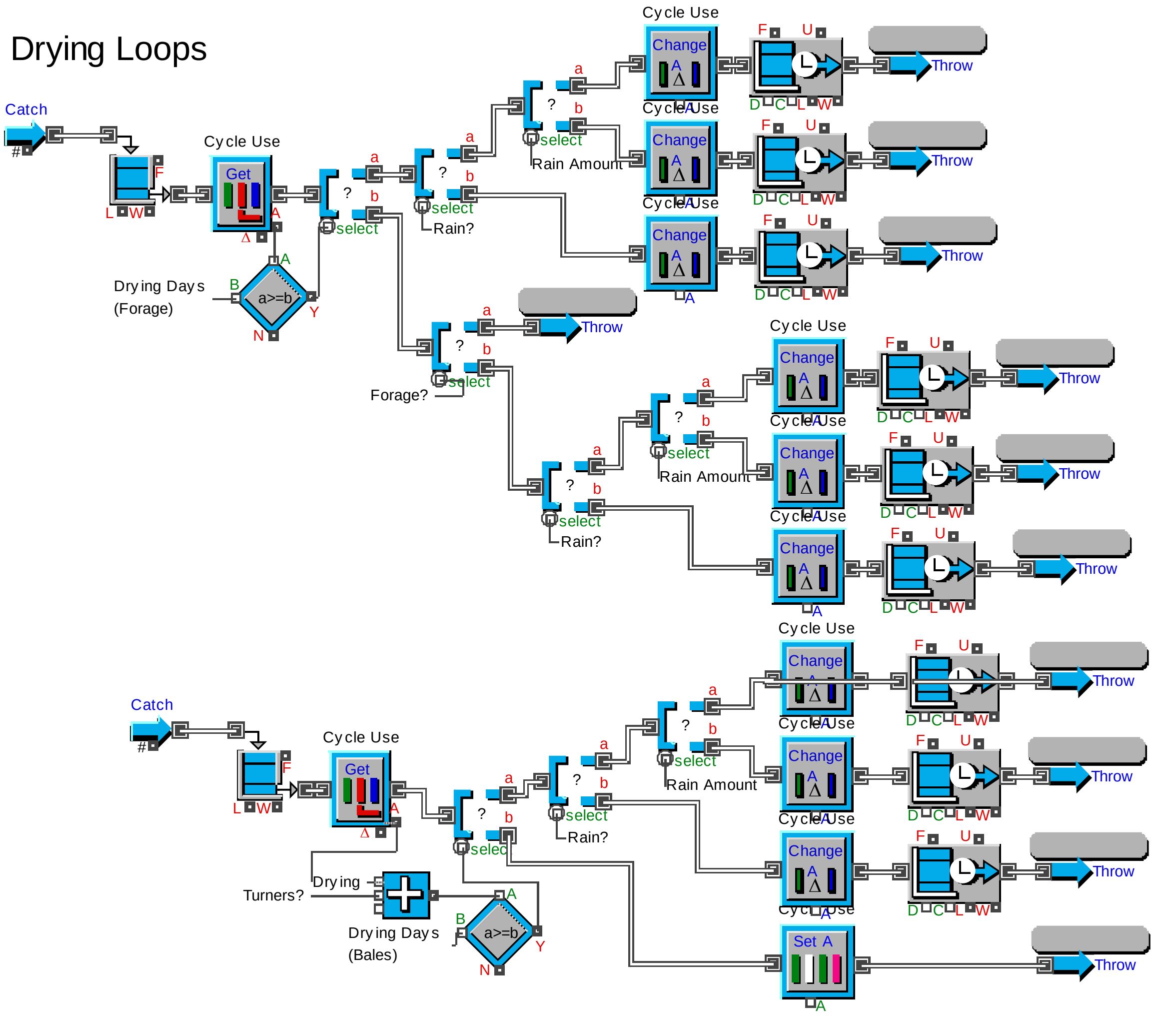
Growth Test



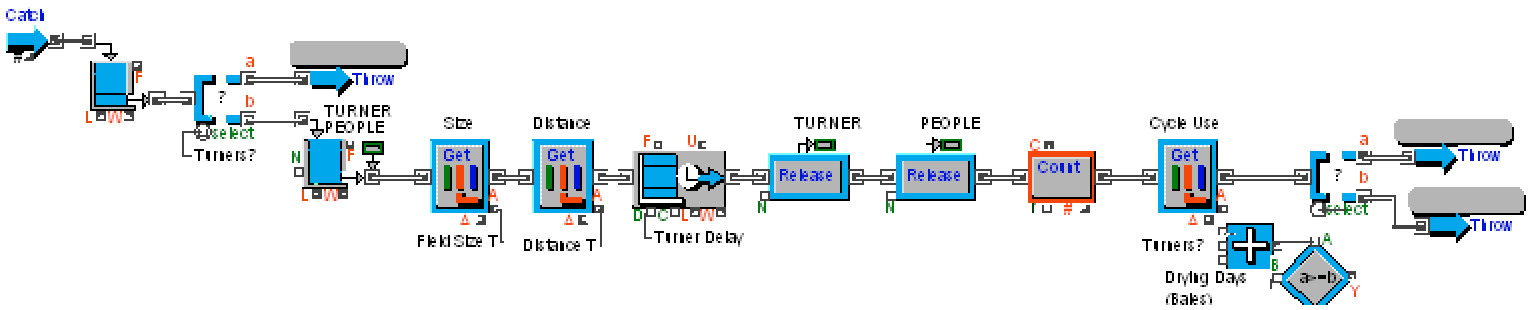
Mowing Loop



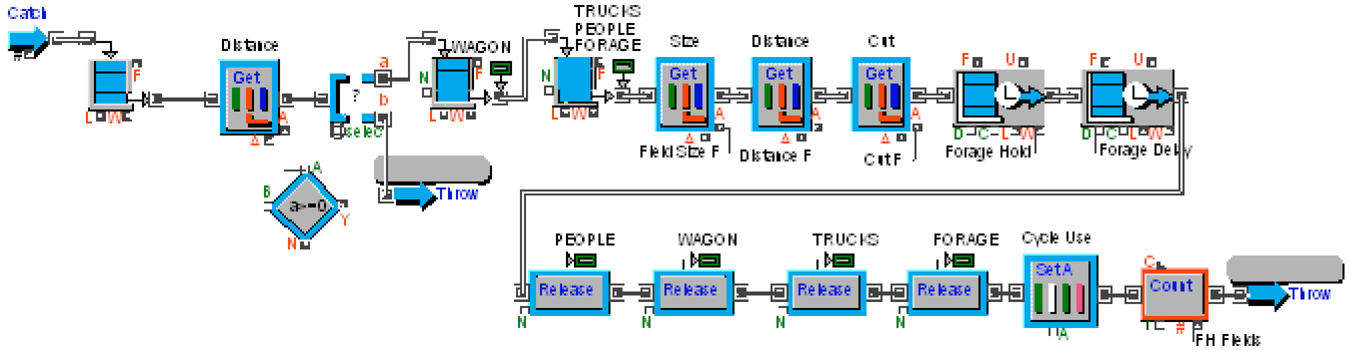
Drying Loops

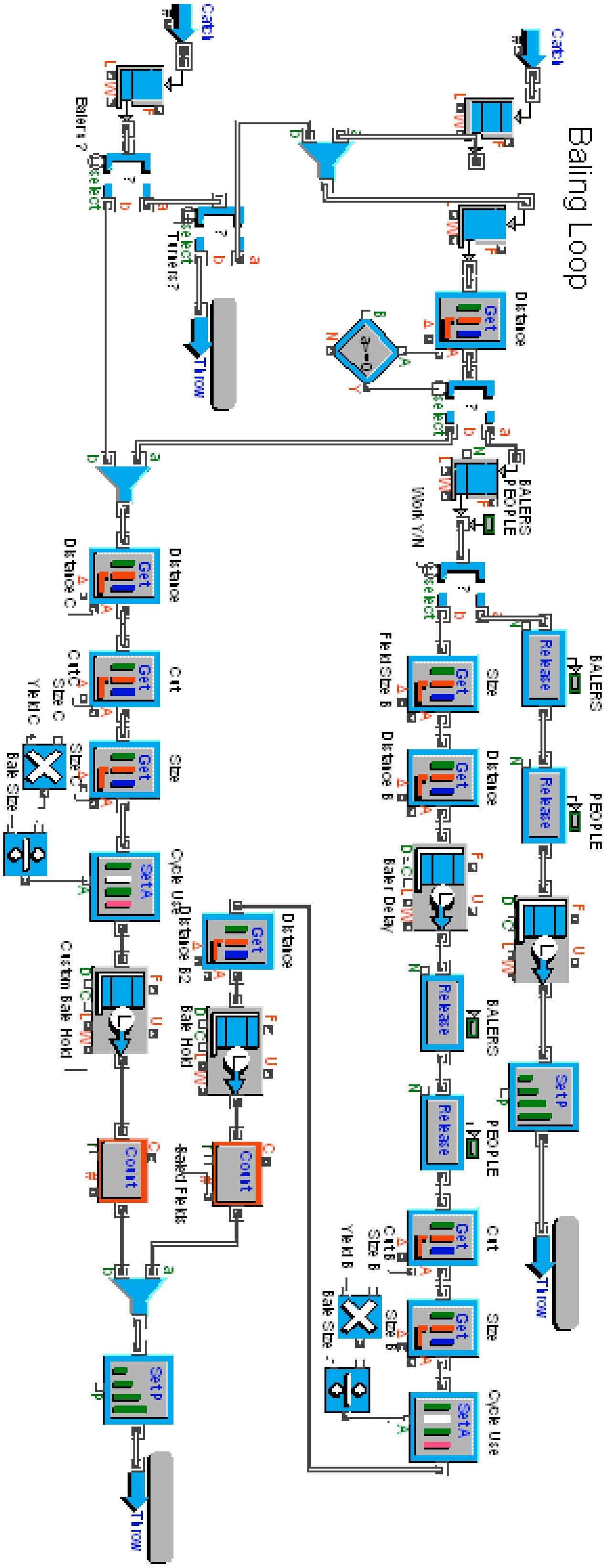


Turning Loop

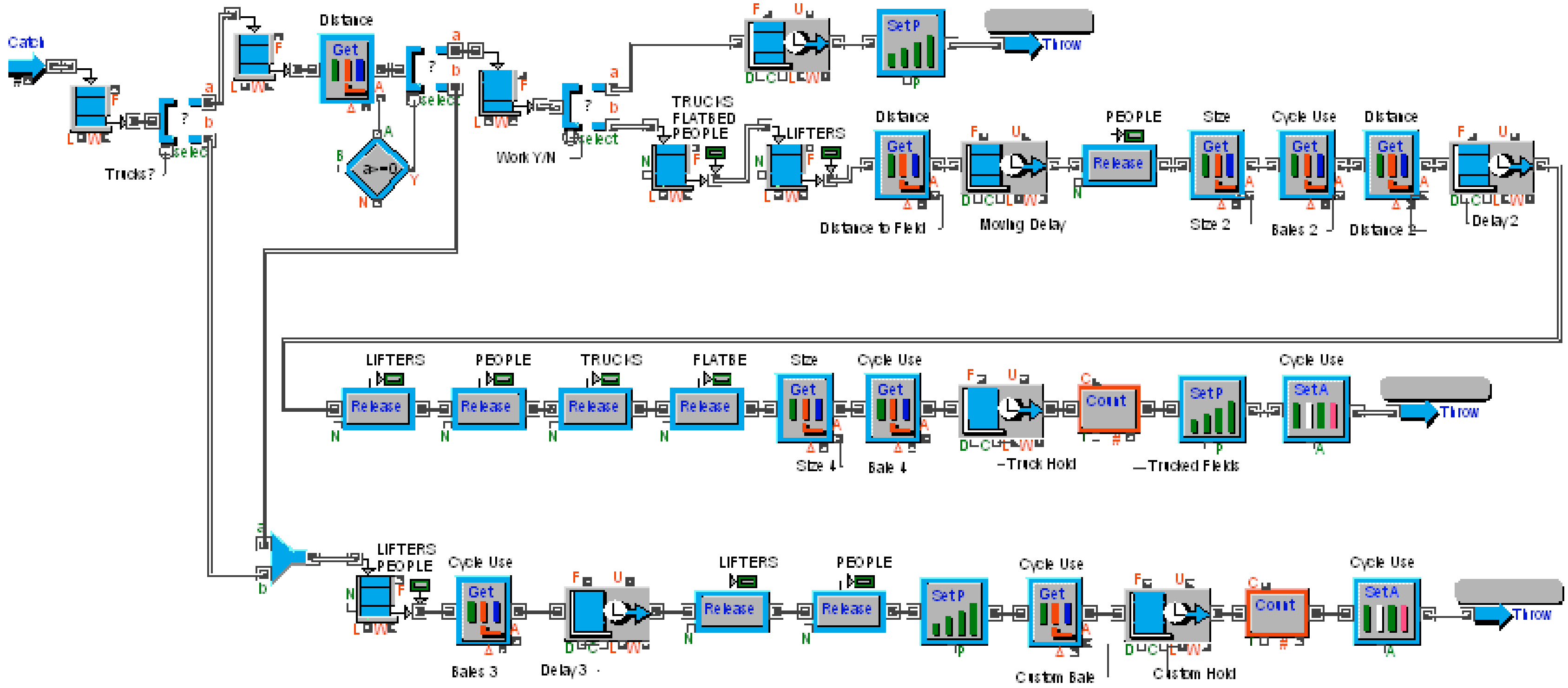


Forage Harvester Loop



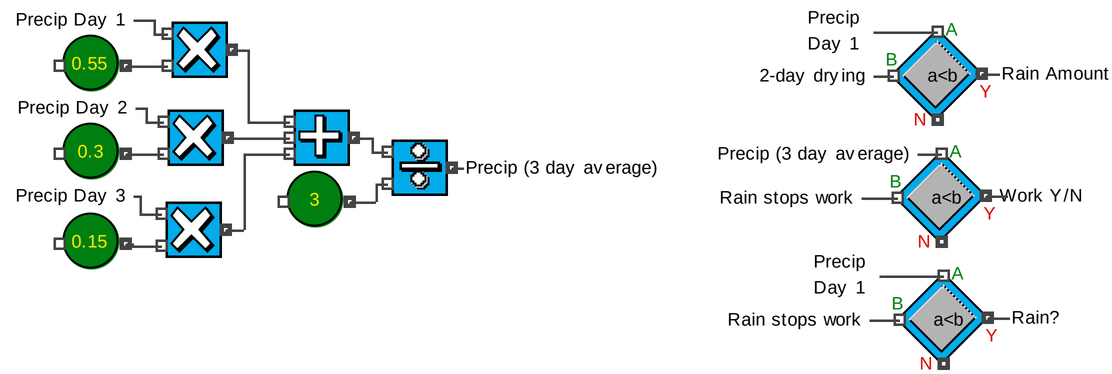

Baling Loop
Catch
Catch
Get
Distance
Select
BALERS
PEOPLE
Work Y/N
Release
BALERS
Release
PEOPLE
SetP
Throw
Size
Field Size B
Distance
Distance B
Baler Delay
Release
BALERS
Release
PEOPLE
Crit
Crit B
Size B
Yield B
Size
Bale Size
SetA
Cycle Use
Balers?
Timers?
Throw
Distance
Distance C
Crit
Crit C
Size C
Yield C
Size
Bale Size
SetA
Cycle Use
Custom Bale Hold
Distance
Distance B2
Bale Hold
Count
Baled Fields
Count
SetP
Throw

Transportation

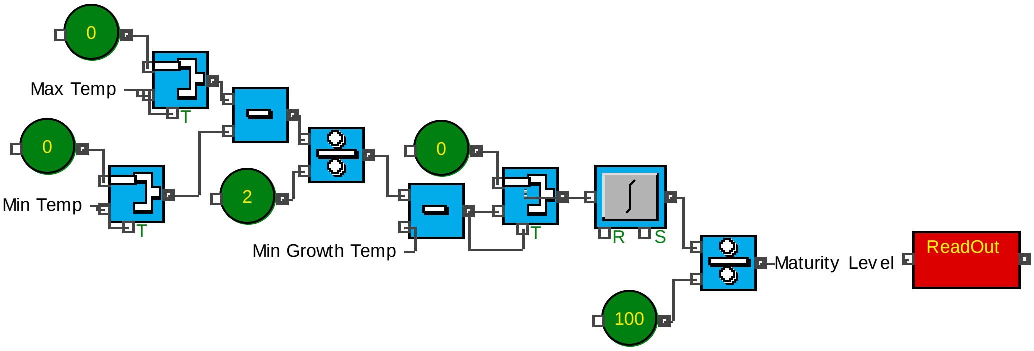


Delay Calculations

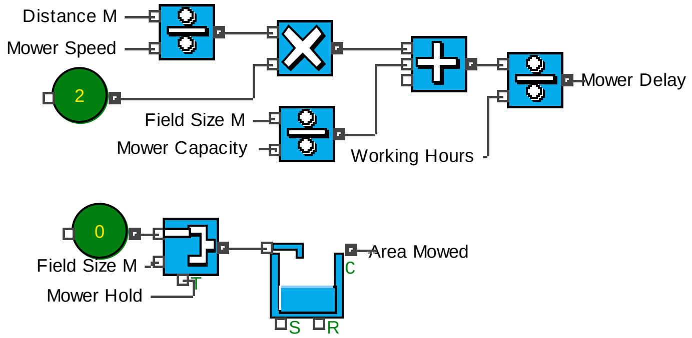
Rainfall Calc's and Decisions



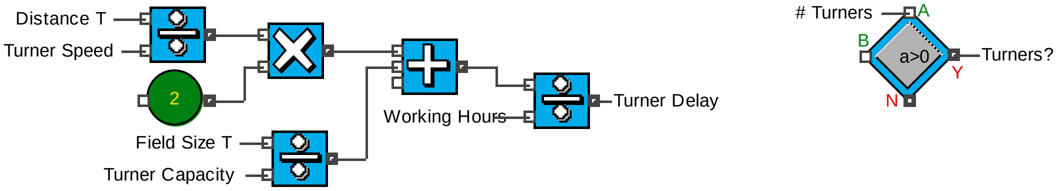
Growth Calculation

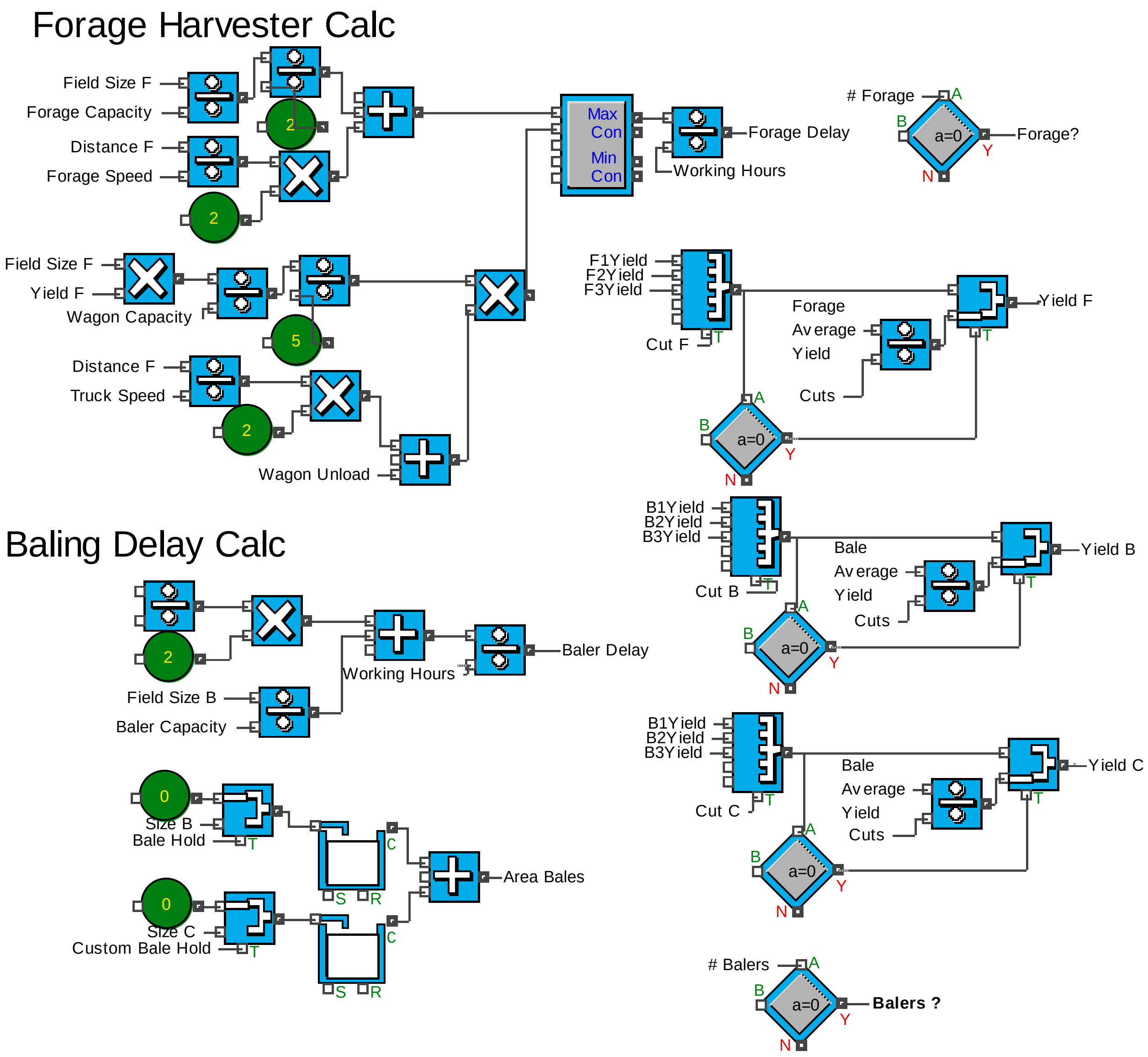


Mowing Delay Calc



Turning Delay Calc




Forage Harvester Calc
Field Size F
Forage Capacity
Distance F
Forage Speed
2
2
Max Con
Min Con
Forage Delay
Working Hours
Forage
A
B
a=0
Forage?
Y
N
Field Size F
Yield F
Wagon Capacity
5
Distance F
Truck Speed
2
Wagon Unload
F1Yield
F2Yield
F3Yield
Cut F
T
Forage
Average
Yield
Cuts
Yield F
T
A
B
a=0
Y
N
Baling Delay Calc
2
Working Hours
Baler Delay
Field Size B
Baler Capacity
B1Yield
B2Yield
B3Yield
Cut B
T
Bale
Average
Yield
Cuts
Yield B
T
A
B
a=0
Y
N
0
Size B
Bale Hold
T
C
S
R
Area Bales
0
Size C
Custom Bale Hold
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C
S
R
B1Yield
B2Yield
B3Yield
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Average
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Balers
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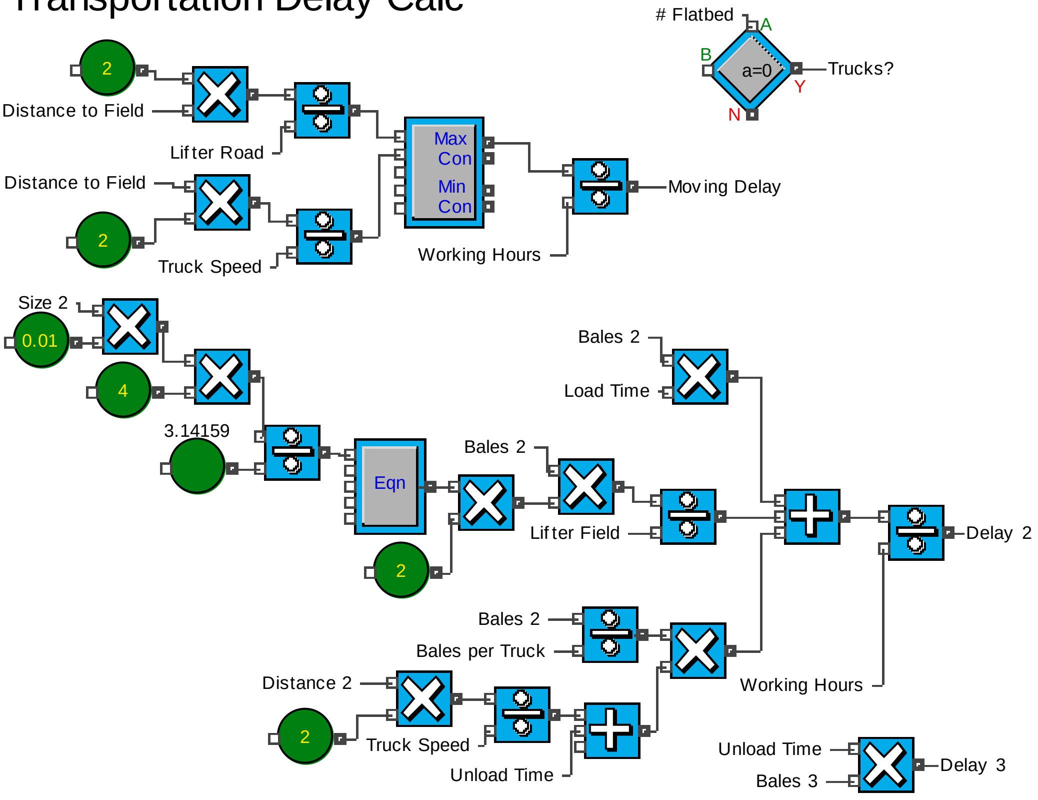
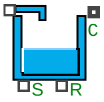
a=0
Balers ?
Y
N

Transportation Delay Calc



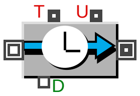
APPENDIX 5 –BLOCK DESCRIPTIONS, DEFINITIONS AND EQUATION SYMBOLS

Block Definitions



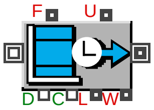
Accumulate

This block sums the inputs that enter the block at each event or time. The running total is output.



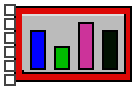
Activity, Delay

This block delays items for an amount of time specific to each item. It can only hold single units.



Activity, Multiple

This block delays items for an amount of time specific to each item. It can hold multiple items for varying amounts of time.

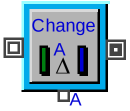


Bar Chart

This block shows the relative outputs of up to 6 factors in the form of a bar chart.

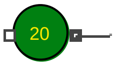
Catch

This block "catches" items sent from a "Throw" block. This allows items to move to sections of the simulation that are not connected by lines. The block can "catch" items that have been "thrown" from many throw blocks.



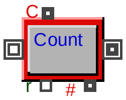
Change Attribute

Changes the value of the specified attribute. The attribute can be incremented, decremented, multiplied, divided or changed to a specified value.



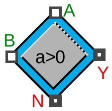
Constant

Inputs a constant value. Double clicking can open the constant block. When the constant block is opened, the user can read the description of the constant and change it accordingly.



Count Items

As items pass through the block they are counted. The number of items is reported in the exiting block.

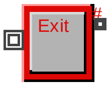


Decision

The decision block makes a decision based on the inputs A and B. It compares the two values and then outputs a True or False (1 or 0). It can make the decision based on the values being greater than, greater than or equal to, equal to, less than, less than or equal to, and not equal.

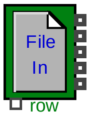
Executive Block

The executive block is the clock in the program. This block must be placed at the top left corner of the model. It determines when the model has run out of time or the maximum number of events has been reached.



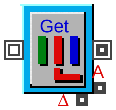
Exit

When items pass through this block they leave the simulation.



File In

This block reads from the specified file. To change the file double-click the block, change the file name and press "read".

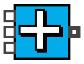


Get Attributes

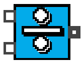
This block reads the value of the specified attribute as the item passes through.

Mathematical Blocks

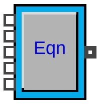
Add



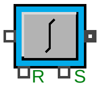
Divide



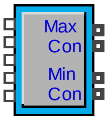
Equation



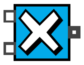
Integral



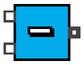
Max & Min

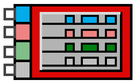


Multiply



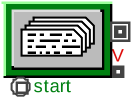
Subtract





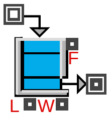
Plotter, Discrete Event

This block plots the values of up to 4 inputs over the time frame of the simulation.



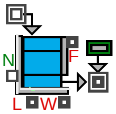
Program

This block generates items based on time frame specified in the block. To change the number of items generated, double-click on the block and add or subtract items in the table.



Queue, FIFO

This is a first-in-first-out queue. Items exit this queue in the same order in which they entered. Items wait in this queue until a space opens up for them further along in the simulation.



Queue, Resource Pool

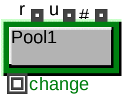
This queue works similarly to the FIFO Queue. However items wait in this queue until the resources that are requested are available for the item.

Read Out

This block shows the value of the input at the end of the simulation.

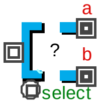
Release Resources

When an item passes through the release resource block the resources are sent back to the resource pool.



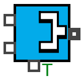
Resource Pool

The resource pool holds and stores resources until they are called for later in the model. The resources are any items that are called on in specific sections of the model rather then traveling through the model. (Fields and days travel through the model, they are not resources. People and equipment are called upon at various times, they are resources.)



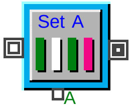
Select DE Output

This block directs items based on the value at the "select" input.



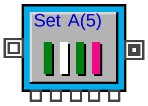
Select Input

Chooses the input based on how "T" compares to the critical value in the block.



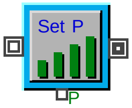
Set Attribute

This block assigns a value to the specified attribute.



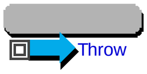
Set Attribute (5)

This block assigns values to as many as five attributes when as item passes through.



Set Priority

This block sets the priority of the item.



Throw

This block tosses an item to the specified "catch" block. This allows the items to move without connectors.

Definitions

Attributes – these are values that are associated with the items that pass through the simulation.

Item – an object that passes through a model

Model – refers to the collection of blocks that were put together by the author, may also be referred to as the simulation.

Program – refers to the EXTEND© modeling program developed. For more information please visit www.imaginethatinc.com.

Resource – an object that is called upon when an item passes through the model.

Equation Symbols

τ = real transport distance in relation to straight line distance (tortuosity factor)

Φ_j = the fraction of the circle occupied by product fields

$1/n_j$ = sectorial fraction of the circular area with raw material fields

AR = application rate of chemical solution

B = number of bales in a field

BT = number of bales per truck load

DAY = 1 for first day, 0 otherwise

DB = dry bulb temperature

Delay = amount of time the equipment is used and the field is delayed (days)

d_{ij} = distance from field i to storage are j

DR = drying rate

EC = equipment capacity (ha/h for most equipment, t for wagons)

EN = number of pieces of equipment

FD = distance from facility to field (km)

$_{FH}$ = forage harvester

Fixed = fixed costs associated with the system

FS = size of field (ha)

H = average working hours in a day (h/day)

HU_i = heat units accumulated on day i

HUI_j = heat unit index (0 to 1)

HU_k = daily accumulation of heat units (cannot be negative)

I_O = initial cost of a piece of equipment

$_L$ = lifter

LT = load time per bale (hours)

M = moisture content

MAX = the maximum value of the two options presented

M_e = equilibrium moisture content

M_o = initial moisture content

N = day

n = time (year)

Other = other fixed costs (insurance, taxes, etc.)

PHU_j = potential heat units required for maturation of the crop

r = rate of return (decimal)

R_j = radius of the circle around storage site j

RS = road speed of equipment (km/h)

SD = swath density

SI = solar insolation

S_j = supply of material in the storage area j

SM = soil moisture content

SV = salvage value of equipment

T = time

$_T$ = truck

$T_{b,j}$ = temperature for crop j below which there is no growth

$T_{mn,k}$ = minimum temperature on day k (deg C)

$T_{mx,k}$ = maximum temperature on day k (deg C)

UT = unload time per truck load (h)

$_W$ = wagon

w.b. = wet basis moisture content

WU = wagon unload time (h)

x_i, y_i = coordinates of field i

x_j, y_j = coordinates of field j

Y = yield (kg/ha)

Y_s = average yield of material (kg/ha)