Master’s Thesis

Smart logistics and supply chain networks for green biomasses

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ABSTRACT

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A mixed-integer nonlinear programing model with three objective functions was developed in order to better estimate the costs regarding biomass logistics, environmental impacts and energy consumption throughout the system. The overall purpose was to minimize the costs, environmental impacts and energy usage associated with all steps of biomass production and transportation from source site to biorefinery. A mathematical formulation of the problem was elaborated. The results from optimization model was set as input to the simulation model in order to gain the operation’s schedule for different farm activities. An interface form was also provided to collect input data from user and integrates the simulation and optimization models. The biomass production uncertainties regarding the changes in prevailing weather condition and fluctuation in the moisture content of biomass was addressed by formulating the scenario-based models. The multi-objective optimization model was coded in LINGO software and solved by applying fuzzy program method. The simulation model was implemented in the ARENA software and the tool’s interface was coded by VBA in Microsoft Excel.
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1 INTRODUCTION

1.1 Biomass and bioenergy
Nowadays, humans are interested in using renewable and sustainable energy sources instead of fossil fuels. Biomass as an interesting source of renewable energy can be obtained by living organisms (Saidur et al., 2011). Currently, bioenergy can provide approximately ten to fourteen percent of required energy throughout the world which has a potential to improve this rate (Kheshgi et al., 2000; Parrika, 2004; Balat and Ayar, 2005; Demirbas, 2005; Oregon, 2010). Availability of different types of biomass, the perfection of conversion technology and reduction of carbon emission are among several factors that turn biomass to an interesting source of energy in the Europe (EBTP, 2006; McCormick and Kaberger, 2007; An et al., 2011). However, there are some challenges regarding the use of biomass to produce energy such as low power density as well as high logistics costs (Thornley, 2006; Saidur et al., 2011). Harvesting biomasses, collecting residues, pretreatment, storing biomasses and transferring them to the biorefinery are 5 main steps in every biomass supply chains which is depicted in the figure (1) (Iakovou et al., 2010).

![Figure 1. Operational steps of a biomass supply chain](image)

1.2 Logistics and supply networks for green biomasses
Logistics of biomass as the main objective of this study includes the activities such as transportation, distribution, storage and handling of biomasses. The existence of biomass market, the accessibility to this market and the supply logistics can affect the whole biomass supply chain. Minimizing the overall costs, reducing the environmental impacts and confirming the continuous feedstock supply are among the main objectives of biomass supply chains (BSCs) (Gold and Seuring, 2011).
1.3 Research problem, objectives and delimitation
The existing logistics assumes fixed quantitative of ready-to-deliver raw materials at each delivery point. The dynamics and optimization possibilities of the supply chain have not been sufficiently addressed in previous research and development efforts, like ignoring the challenges and tradeoffs associated with performing these functions in the supply chain. Therefore, a pervasive modeling method required for expanding an operational, interactive and adaptive tool for projecting and analyzing the total transport logistics as well as its yield, economic viability and environmental impacts.

This approach will ensure proper considerations of the various types of production, low-density material (high costs per ton-km), challenges in handling feedstocks, resource inputs, environmental impacts and seasonal availability.

The key objectives include:
- Evaluate the possibilities of reducing the costs of handling and increasing system performance from harvesting to delivery at the production facility.
- Recognize important cost elements, possible logistic pinches, and other opportunities for operational chain optimizations.
- Develop an interactive operational tool for analyzing and simulating enhanced transportation logistics in terms of identifying optimal supply system elements, different machinery chains, management strategies and facility locations.
- Integrate the overall logistic systems with the farm operations.
- Integrate the logistical system with the timeliness and workability of the harvesting of energy crops.

1.4 Research methodology
Based on the literatures reviewed and empirical data, the required information to modeling and simulation were obtained. Regarding the optimization and simulation model, an operational, interactive and adoptive tool will be provided to plan and analyze the overall transport logistics and its efficiency, economic viability and environmental impacts of the logistics of biomass supply chain.
Different scenarios will be analyzed to test the different harvesting and transport systems and operational feasibility under a variety of different logistics constraints. The influences of harvesting workability and weather restrictions, crop yield, harvesting technology, density of transported materials, transporting equipment will be evaluated on empirical data sets. These data sets include comprehensive normalized labor and machinery performance data, energy consumption data, historical weather data. In addition, the evaluation will include the identification of key parameters and sensitivity analysis on these parameters. A brief schematic view of the research methodology, which applied in this work, is demonstrated in the following figure.

Figure 2. Research methodology

1.5 Organization of the study
The remainder of this research is organized as follows: the second part discuss about the several aspects of biomass and bioenergy and presents useful information about the biomass logistics and biomass supply chain. In third part, the methodology of the research covered in detail and all the information regarding the definition of the problem and solution is given with two approaches. Part four presents the calculations regarding machine performance and other parameters which applied in the model. Part five provides useful information regarding modeling approaches that is considered in this study. Part six provides the development of the mathematical model and discuss
about different aspect and assumptions regarding the model. Furthermore, the mathematical models developed under alternative scenarios and the revised formulation of the model presented. Moreover, in this part, the simulation model is described in detail and all the sub-models depicted to give clear understanding of the system. In part seven, the assessment tools were described in detail and the interface forms also depicted with some explanations. Finally, in chapter eight, the results related to each parts of the study presented and different sensitivity analyses were designed to examine the effects of alteration in parameters and variables on objective functions.
2 BIOMASS

Biomass as an organic matter is gained mostly from plants and it uses in various locations as a source of green energy. Biomass can be converted directly to the heat or it can be transformed to several types of biofuel.

2.1 Background
In the following parts, several related issues regarding the biomass and logistics of biomass is presented in detail.

2.1.1 Biomass to biofuel
Biomass transformation processes can be arranged into three different sets: thermal, chemical and biochemical methods. Biofuels can be classified into two groups, bioethanol and biodiesel. Based on figure (3), bioethanol can also be divided into two sets, the first generation, and the second generation. The first-generation bioethanol is based on the biomasses containing sugar and starch like Corn, Sugarcane, Maize, Molasses, and Sorghum. The second generation of bioethanol is based on several biomass resources such as agricultural residues and livestock products (corn stover, wheat and rice straw and bagasse), urban woody waste and landfills, forest biomass, herbaceous energy crops (Switchgrass, Miscanthus, Reed canary grass, Alfalfa), and short rotation woody crops.

2.1.2 Characteristics of biomass
Dispensation in a low quantity over a wide area, diverse quality with approximately high content of moisture depends on the various types of biomass, seasonality and lower energy content than fossil fuels are among several characteristics of biomass. Generally, developing an efficient biomass supply chain network with an effective collection method, preprocessing, storage and transportation system is a challenging work (Yue, You and Snyder, 2014).
2.1.3 Seasonal supply and storage

Seasonality and annual fluctuation of biomasses are usually critical issues in the biomass supply chains (BSC). Majority of biomass feedstocks are growing materials, which required to be seeded, tilled and harvested. According to the study by Sokhansanj et al., 2009, a careful planning and scheduling required having an expected quality and quantity of feedstocks. Therefore, managing the biomass feedstocks to have a continuous supply is a complicated issue.

2.1.4 Decaying and Pretreatment

Biomass decaying, heating value cutback and possible health risks usually occur due to a high-water content of biomass feedstocks. Therefore, a closed storage site with a drier system can improve the quality of biomass supply (Cundiff, Dias, & Sherali, 1997). Making a decision about the location of storage facilities is a challenging task because it requires a tradeoff between warehouse expense and material waste. Moreover, pretreatment is usually applied before the storage of biomass feedstocks to decrease the dampness, eliminate pollutants and enhance the quality and steadiness of biomass feedstocks. Based on the study by Uslu, Faaij, & Bergman, (2008), pretreatment processes can be classified into four common types: physical (e.g. mechanical...
sheering, freezing/thawing), thermochemical (e.g. pyrolysis, ammonia fiber explosion), biological (use of microbes or enzymes) or others (e.g. Irradiation).

2.1.5 Biomass Yield
The biomass yield defined as the capability component of a crop with production levels based on a certain environmental condition and cultural practices. It can be also termed as the biomass in an area at a given time of the standing crop. Usually this term used with fresh or dry weight which determined the amount of produced biomass. Grain yield data were considered to evaluate the process of producing feedstocks. The remnant yield (ton/ha) can be assessed by the biomass to grain ratio (Perlack et al., 2005).

2.1.6 Biomass Logistics
A considerable attempt is required in the selection of equipment, managing the shifts and scheduling the fleets that make the biomass logistics a demanding work (DOE/EERE, 2013). Biomass supply chain logistics consists of all the processes from harvesting to transferring the biomass into the biorefineries. Basically, the progressing of operations in BSCs are based on the dampness and the shape of residues (particles length and wrapping). In this regard, biomasses can be classified into two groups, dry or wet biomasses. Dry biomasses such as straw, stover, dry grasses and dry wood chips have a moisture content of less than 15-20%. However, wet biomasses like moist straw, forage and wet plant shavings are defined as materials with dampness of more than 20%, which require preprocessing (drying) before storage, or it could be stored in the silage format. Further, no preprocessing is needed to store biomasses in bale format because they are usually dry (Mielenz, 2009).

2.1.7 Biomass production
Biomass production process involves all the operations from planting to harvesting the feedstocks. In this process after planting the crop, it can be used as a primary product like grain and the remained residues after harvesting can be used for bioenergy. Strategies like changing crop rotation can be used in bioenergy production to improve the availability of crop residues. It should be considered that in integrated feedstock supply system, whenever the biomass is ready for harvest, the crop production is needed there (Mielenz, J., 2009).
**Biomass energy conversion**

Converting biomass to the heat and power energy and producing biofuels from sugar, starch and oil seeds are very common processes in biorefineries. The decision-making about biorefineries is usually based on the allocation of conversion plants, conversion technology selection and capital and operational planning of plants. In biomass supply chain, types of crops and the desired final products can define the technologies applied in biorefineries. Several resources such as forests, agriculture and waste can obtain refinery biomasses. Figure (4) depicted the classification of the biorefineries types.

![Biorefinery types diagram]

Figure 4. Biorefinery types

2.1.8 Dry matter loss

Feedstocks decrement happen in different steps of harvesting and storage processes. Generally, wastes of dry materials can be classified into two groups: First, losses during the operation of facilities and second during the pause before starting the next operation. Feedstocks wastes during the operation of facilities are mostly related to physical parsing of materials to a degree that cannot be possible to be gathered. This kind of wastes depends on several factors such as the moisture content of field during the harvesting process, output, physical properties of the plant, design characteristics of the facilities and dominant climate situation. In addition, chemical wastes can take place because of dissociation of structural carbohydrates (Mielenz, 2009).
2.1.9 Environmental Impacts

Nowadays the topics such as environmental sustainability have received high notice from the societies. The life cycle assessment (LCA) as an outstanding option is very useful in evaluation and analyzing the negative impacts of systems products on the environment (Azapagic, 1999).

Assessment method

To assess the negative effects on environment, LCA that was defined above is translated per each damage assessment models. The GWP as a common measure of LCA focuses on greenhouse gas (GHG) emission (IPCC, 2007). Based on the researches by Goedkoop and Spriensma (2001) and Humbert et al. (2012), Eco-indicator 99 and IMPACT 2002+ are two metrics, which can evaluate the environmental impacts in a wide category. Moreover, the trace of remained water from biorefineries is another critical problem in BSCs design (Bernardi et al., 2013).

2.2 Biomass supply chain processes

The main objectives of each BSCs are keeping the biomass costs competitive (Hess et al., 2007) and ensuring the nonstop biomass supply (Sims and Venturi, 2004). The following parts defines the processes belongs to the biomass supply chain. The following figure depicts the common steps in a biomass supply chain.

![Biomass supply chain](image)

Figure 5. Biomass supply chain (Batidzirai, 2005)
2.2.1 Harvesting and collecting biomass

Harvesting can be defined as a process of cutting crops in a field. Harvesting as a labor-intensive process, required special farm machineries and in large mechanized farms this process is costly for farmers. Collection can also be defined as a process of gathering harvested residues and packing them in order to transfer feedstocks to the biorefinery or storage places.

The main decision regarding harvesting and collection processes can be listed as finding the optimal location of land, harvest scheduling and planning the biomass collection based on the moisture content of biomass, weather condition, land availability and bioenergy demand.

Drying, baling and chipping are the most common options, which follow the harvesting processes. Chipped biomass can be directly converted to the energy or transported for longer distances in the form of pellets (Hamelinck et al., 2005). Based on the study by Hamelinck et al., (2005), baling is a useful process that can enhance the biomass density and facilitate the handling of biomasses through the logistics operations as well as decreases the risk of biomass spoilage (Forsberg, 2000).

Properties of biomass which affect the harvesting/collecting processes

Some special characteristics related to biomasses makes harvesting processes costly such as disperse geographical distribution of biomass resources (Gronalt and Rauch, 2007). In some countries like Denmark and Austria, the logistics cost rises due to disintegrated supply areas of biomasses (Möller and Nielsen, 2007). Moreover, the seasonality of most biomass types brings short harvest period for them (Caputo et al., 2005). Because of once annually harvest, there is a remarkable low usage of invested money on devices and facilities (Hamelinck et al., 2005). According to Uslu et al., (2008), limited harvest period requires more inventories, which can increase the storing expenses and dry material waste.

Harvestable biomass

Usually, the biomass crops cannot be harvested totally due to issues related to the erosion control of the field and it hinge on several aspects like the texture of dust as well as the slope of the ground. Accordingly, coarse texture soils needed more surface residues to control the wind erosion effects. Moreover, the number of remained residues to deal with the water erosion effects, increases by enhancing the slope of the field (Campbell et al., 2002). Based on the research by Campbell and Coxworth (1999), this amount of surface residues is about (1300 kg/ha) of biomass crops which
should have remained on the surface of fields to control the soil erosion effects. Based on the results of study by Kline (2000), 30-50% of crop residues should be left to handle the wind and water erosion problems.

**Harvesting modes**

Harvesting defined as a process of cutting the crops and performing some required preprocessing steps. These steps include several processes such as conditioning, putting biomass into a windrow for later collection and drying purposes as well as threshing and separating the biomasses. During harvesting steps, biomasses can be collected into different shapes such as chopped, baled or directly into large stacks to progress the bulk density of biomasses and decrease the cost of transportation and storage. Several factors influence the selection of biomasses forms such as availability of equipment, crop types and logistics (Mielenz, 2009). Figure (6) demonstrated the possible methods for collecting residues from a source site.

![Figure 6. Options for biomass collection (Mielenz, 2009)](image)

**Mowing and conditioning**

The term mowing refers to a method of picking the crop and conditioning is a kind of operation, which facilitates the drying processes of cut plants. Special equipment such as mower conditioner has an ability to utilize both mowing and conditioning simultaneously. There are various operations such as crimping, crushing (super conditioning), raking, tedding and swath inversion...
which can facilitate the drying process. However, crushing is not appropriate for wet environment due to increasing the rate of moisture absorption (Mielenz, 2009).

**Chopped form biomasses**
Biomass crops can be harvested into three shapes: baled format, chopped form or loaf shape. In this process, a forage harvester collects the residues, chops them to pieces, and gathers them into a carriage. As a characteristic of this machine, it can operate automatically or dragged and worked by the power of a tractor. Moreover, this machine can be equipped with different forage cutting heads based on the type of crops. Furthermore, it should be considered that decreasing the cut length induces smaller size of residues particles at the expense of increasing chopping energy per ton. After harvesting, the chopped biomass can be handled by forage wagon or trucks. For wet crops, all the gathered feedstocks transferred to the fields sidelong and stored in a bunker or silage bag to accelerate the fermentation process (Luginbuhl et al., 1979).

**Baled form biomasses**
Regularly, biomasses are harvested in the form of bales. Biomasses can be formed into two shapes bale: round or rectangular. Usually, round bales characterized by the weight range of 250 to 1087 (kg) in diverse sizes from 760 (mm diameter) * 1000 (mm length) to 1900 (mm diameter) *1570 (mm length) (Cundiff, 1996). A big rectangular shaped bale has a size of 1.2 m *1.2 m *2.4m. The small bales are more applicable for biomasses. These types of bales are more efficient in space usage as well as can be squeezed to be bulkier. The best benefit of using rectangular shaped bales is that the maximum capacity of trucks can be used. These bales weighed in the range between 500 kg to higher than 900 kg regarding the type and moisture content of feedstocks. Normally, baling machines are operated by the power derived from the tractor that dragging them whose minimum power is 140 KW (Srivastava et al., 2006).

**Stacked form biomasses**
This method as a conventional forage transferring technology applied to handle the large volume of biomasses in stack wagons. Dry residues collected by stack wagon and stored in a container. Based on the study by Anonym, (1987), these containers have a size of about (2.4 m width * 6 m Length* 3.6 m height) with a movable roof to applied force on the stored residues to enhance the
density of collected materials. The process of gathering biomasses pauses while the compression cycle starts. Therefore, the yield of stack wagon decreases because of these pauses. Moreover, by appearing the modern huge balers, the application of loose stacks for handling the biomasses was ceased (Kumar and Sokhansanj, 2007).

2.2.2 Storage throughout the bioenergy chain

Storage processes often exist throughout the BSCs to match the biomass supply with bioenergy demand. Furthermore, limited harvesting period can also oblige farmers to have more storing facilities (Uslu et al., 2008). Principally, closed type storage facilities near the biorefineries are favorable to use in order to decrease the costs of handling (Hamelinck et al., 2005).

**Storing cost**

According to Van Belle et al., (2003), storing expenses mostly affected by the position of facilities and sort of storage equipment. Moreover, the rate of dry material waste of solid biomass can increase by rising the quantity of storage steps throughout the BSC (Hamelinck et al., 2005).

**Storage options**

Storage facilities can be located at various distances from the biorefineries such as near the harvest site, at the roadside or at some collecting points near the biorefineries (Hamelinck et al., 2005). Storage types can be classified into several methods such as open air, roof covered, air fan and so on. Based on the study by Van Belle et al., (2003), biomass procession and weather condition are two factors that influence the selection of storage types. If baling system is considered, after transforming biomass into bales, both types of storage (open or closed) are sufficient. In general, in rainy weather round bales can tolerate more moisture than square bales, which are appropriate for pile up and required to be stored in covered places (Haq and Easterly, 2006).

Due to frequent changes in harvesting period and its outputs, biomasses required being stored to ensure the stable supply all over the year. Dry mode of biomass stocks in bales format can accelerate the storing process more than the wet mode. However, some key issues related to the storage of dry biomasses should be considered such as dry matter loss, the decadence of feedstocks and quality alteration. To decrease the side effects of wet biomasses, the moisture content of materials should be less than 15%. In addition, some methods can be applied to decrease the wastes
of sugar output in storage processes such as proper storage methods, stack shapes and preservative hindrances. Moreover, fire risk as a common issue should be considered in the design of dry storage system (Mielenz, 2009).

The common decision making regards the storage process refers to the selection of storage facilities and their capacities. Several factors influence the facility allocation decisions such as the type and properties of biomass feedstocks and the transportation constraints (Allen et al., 1998). In addition, the role of midway storing site was considered by using a dynamic discrete event simulation (Nilsson and Hansson, 2001). Papadopoulos and Katsigiannis (2002) deemed the possibility of locating storage facilities next to the biorefineries by applying a dynamic programming approach to minimize the total storage costs of biomass feedstocks.

2.2.3 Transportation in bioenergy chain

Transportation as a cost factor of biomass supply chain is very important owing to the differences in energy compression of biomasses comparing to fossil fuels (Mayfield et al., 2007). Transportation laws, infrastructural and special properties of roads are among the key issues should be considered in BSCs logistics (Mayfield et al., 2007; Leduc et al., 2009; Möller and Nielsen, 2007).

Integer linear programming was applied by many researchers to specify the best transportation strategies according to the constraints of biomass availability, transportability and biorefinery demand (Busato and Berruto, 2008). A GIS-based model developed by Frombo et al. (2009) to find the minimum cost related to supply networks of woody biomass. Ravula et al. (2008), in addition, developed a simulation model (discrete event type) with two proposed approaches for arrangement the vehicles in a BSC. The outcomes of this paper indicate that scheduling based on travel time leads to lower total costs in contrast with other scenarios. Briefly, several models in the context of biomass transport were developed due to determining the eventuality of alternative routes, selection of transport facilities (types, capacity and planning), minimizing supply network expenses, reducing transport duration and limiting the negative impacts of BSCs on environment. Feedstocks are carried and transferred several times during the biomass supply chain. If the collection processes were considered, usually biomass handled from the plant to sides of the field or to the storage hubs. Biomass can also be transferred to the biorefinery or may be delivered to the preprocessing units before transporting to the biorefineries. Different modes of biomass
transferring are applicable based on the feedstocks formats during the transportation process. Determining the optimum length for storage, the required number of transporting operations and the transferring route are among the objectives in this context (Mielenz, 2009).

**Main variables impacting transport operations**
Travel time as one of the main variables in transportation operations is hinging on two parameters, namely, distance and speed. The distance correlates to the traveled path, the amount of cultivated land and its biomass output. The actual distance could be determined by applying optimization methods. Several factors influence the speed such as route properties and infrastructure, flexion of roads, types of transportation (truck, railway, ship, pipeline) and timetable of workload and vehicles (Möller and Nielsen, 2007). Some characteristics related to biomass such as the amount and volume as well as the capacity of containers are considered as important variables of transport. To decrease the costs of transportation, vehicles cycle capacity should be enhanced by utilizing more densified biomasses (Hess et al., 2007; Möller and Nielsen, 2007). Another transport relevant variable is labor costs of vehicle driver that is based on the travel period, the cost of vehicle and the cost of utilized fuel (Gronalt and Rauch, 2007).

**Social and environmental impacts of transportation**
Basically, there is a correlation between the amount of transport emission and the transport distances. Furthermore, the amount of transport emission is considerably affected by the mode of transportation. Traffic congestions because of frequent vehicle transports have negative effects on communities. If the modes of transportation were considered, Rail transport can decrease the number of transportation and improves the efficiency of the logistics system. Based on the study by Searcy et al., (2007), pipeline transportation is also useful but this method is not suitable for transferring the fluid from biorefineries due to considerable losses of heating energy of fluid.

**Key cost components of handling and transportation**
Minimizing the biomass handling and transportation costs can limit the whole biorefinery costs. Therefore, the biomass patch ought to be condensed to decrease the transference expenses. The initial purpose of the biomass supply network is to simplify the share of supply logistics or deduct the production costs of the ultimate product. There are three approaches to attain these goals: first,
proper technology selection to decrease the operational cost of parts. Second, selection of facilities and order of operations to reduce the cost and third is transferring worthy feedstocks to the biorefineries to enhance the output of ultimate products (Mielenz, 2009).

The conventional method of determining the biomass delivery costs consists of two parts: a fixed cost element and a variable cost element. If a truck handles biomasses, then, the fixed cost component is the cost of loading and unloading and the variable cost relates to the consumption of fuels, amortization, maintenance and labor. The table (1) summarizes different cost components of three transportation modes (Marufuzzaman, Ekşioğlu and Hernandez, 2015).

<table>
<thead>
<tr>
<th>Mode of transportation</th>
<th>Cost components</th>
<th>Variable cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>cost of ownership, cost of loading and unloading, license fees and taxes,</td>
<td>fuel consumption, amortization, maintenance and repair, labor, tire costs</td>
</tr>
<tr>
<td></td>
<td>insurance cost</td>
<td></td>
</tr>
<tr>
<td>Rail</td>
<td>rail siding, rail wagons, machines used for loading and unloading feedstocks</td>
<td>rail company charges (capital recovery, maintenance for track and engines),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fuel, operating costs</td>
</tr>
<tr>
<td>Pipeline</td>
<td>construction cost, pipe material cost, road access, booster station cost</td>
<td>pipeline maintenance, pump maintenance, labor cost, electricity cost</td>
</tr>
</tbody>
</table>

The bottleneck in transporting biomass

The main bottleneck in transporting biomass occurs during loading or unloading of transport facilities. For instance, it takes approximately half an hour to load 36 bales in a truck and the same amount of time to unload it. Changing the form of biomass, for example to grinding, can enhance the efficiencies but this change costs more and needs a trade-off between options. There are some densification strategies which are economical than baling systems. Moreover, applying denser types of biomass such as cubes and higher pellet mill yield can reduce the transportation costs. In addition, the availability of several feedstocks for a long period of year is an opportunity to reduce the transportation costs due to decreasing storage expenses (Mielenz, J., 2009).

Overall transport logistics and its efficiency

Collecting and transporting scattered crops, doing pre-treatment for differences in quality, drying the moisture content and storage biomasses due to seasonal factor can improve the efficiency of biomass supply chains. Planting lignocellulosic biomass is a better option than corn or soybean
due to less supplying uncertainty and costs. Furthermore, providing several smaller biorefinery
instead of centralized one large size is a better scenario which reduces the overall supply costs
(Ekşioğlu et al., 2009).

2.2.4 Pretreatment techniques
According to Larson et al., (2010), pretreatment is a kind of process, which improves the biomass
energy conversion rates and simplifies transferring and storage processes. The common
pretreatment processes that applied based on the biomass types is depicted in the figure (7).

Figure 7. Pretreatment types (Stelt et al., 2011)

There are several types of pretreatment techniques such as ensiling, drying, pelletization,
torrefaction, and pyrolysis that can be used based on the biomass conditions before transferring
the feedstocks into biorefineries. In the following table (2), the definition and objectives of two
types of pretreatment methods is presented.

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>Definition and purposes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensiling</td>
<td>The process of creating silage via an aerobic fermentation</td>
</tr>
<tr>
<td>Drying</td>
<td>Reduces the moisture content, increases the efficiency of combustion and gasification processes</td>
</tr>
</tbody>
</table>

A combination of torrefaction and pelletization methods can be a good option to decrease the
logistics costs and enhance the efficiency of energy conversion (Uslu et al., 2008). Moreover,
Chiueh et al. (2012) provided a GIS-based model to assess the cost efficiency as well as carbon
emission in a BSC. The results of this paper indicate that the major share of costs in BSCs belongs
to transportation, and storage activities in pretreatment processes.
2.2.5 Design of the bioenergy production system

Designing the Overall supply chain of a bioenergy system is a key issue in each BSCs. Optimized design of supply chain is required to have an efficient system. Therefore, finding the optimal location of facilities used in chipping or storing processes or functionality of various stages throughout the supply chain are critical actions in the whole system (Gronalt & Rauch, 2007). Biomass supply chain characterized by high level of complexities including various market segments, biomass resources, supply chain parties, conversion techniques, end-use applications, harvesting types, transportation modes, and biomass suppliers as the most important issues within BSCs. Biomass supply chain processes include several steps from planting to transferring biomass to biorefineries (Becher s. et al., 1994). Usually, depends on the types of biomass or used conversion technology, there are some pre-processing steps before transporting the biomass to the biorefinery (Vlachos D. et al., 2008). Decision regarding the facility location plays an important role in the strategic design of BSCs. According to the study by Drezner and Hamacher, (2004), a common facility location problem consists of a group of dispersed customers and several facilities to provide the requests of customers.

Challenges and issues

There are some challenges and issues that influence the design and planning of BSCs, which can be classified into six categories: technical, financial, social, environmental, regulatory, organizational issues (Mafakheri and Nasiri, 2014).

Technical and technological issues

One of the main challenges in each BSC is to certify that biomass is efficiently used in the biorefinery. Based on the research by Adams et al., (2011) biomass resource utilization without planning to replacement planting can result in deficiency of biomass resources due to the seasonality of biomass. From inventory point of view, selection of appropriate storage system regarding the holding costs and associated risks are complicated problems to solve due to uncertainties about the quality and quantities of biomasses (Kurian et al., 2013). Ineffective conversion technologies without a proper maintenance planning of facilities is another challenging issue in biomass supply chain (Saidur et al., 2011).
Financial issues
Diamantopoulou et al., (2011) indicate that a significant portion of biorefinery production costs is derived from harvesting, collection, storage, and transportation costs. Further, a three-stage L.P. model was developed by Frombo et al. (2009) to optimize strategic, tactical and operational costs of BSC. Papapostolou et al. (2011) also provide a MILP model to maximize the net income of a BSC with limitations like biomass demand, land use and water resources. In addition, a multiple objective stochastic optimization model was provided by Gebreslassie et al., (2012), to determine the optimal annual expenses and financial risk of a BSC. The results indicate that, the capability of switching the biomass resources can decrease the financial risks in a biomass supply chain.

Social issues
Minimization of possible conflicts with food supply chains is one of the social challenges in BSCs (Tilman et al., 2009). In this scene, increasing the biomass plantation can reduce the number of lands available for agriculture (Ignaciuk et al., 2006). Based on the results of the study by Koh and Ghazoul, (2008), if the types of biomass, targeted lands and amount of production are considered carefully, many of the related social issues could be removed.

Environmental issues
Reducing GHG emission and utilizing waste as a source of energy production, motivates societies to utilize bioenergy to provide required energy. In this context, sustainability of bioenergy production is a critical issue that should be considered in each biomass supply chain (Banos et al., 2011). Based on the research by Awudu and Zhang (2012), biodiversity damage, land, water resources, flora and fauna, soil loss and natural environment are among the ecological challenges related to biomass supply chains. A discrete-event model was developed by Mobini et al. (2011) to simulate the carbon emission in a BSC. Based on the result of this paper, a balanced delivery strategy with minimum carbon emission and supply chain costs were proposed. Further, a simulation model implemented in Arena software provided by Zhang et al. (2012) to minimize the overall costs, energy used and carbon emission of a BSC.
Policy and regulatory issues
The important challenging issues regarding the policy and regulatory can be summarized into four items: the effect of petroleum tax on transference of biomass, deficiency of motivations to make challenge between bioenergy manufacturers, concentration on technology choices and fewer consideration to different types of biomass resources and deficiency of provision for supportable supply network resolutions.

Official and organizational issues
The important challenging issues in the context of institutional and organizational matter can be classified into different possession regulations and primacies between supply network parties, deficiency of supply network norms, the effect of administrative standards and guidelines on decision-making and supply network synchronization.

2.2.6 Biomass Supply chain decision levels
Generally, BSC decisions can be classified based on their level of significance into three distinct types. Furthermore, there are some considerations in the strategic decision to gain competitive advantages such as supply chain configuration, resource allocation, selection of production technology and demand contracts (Iakovou et al., 2010). The following figure demonstrates the classification of supply chain decisions.

Figure 8. Decision levels (Mula et al., 2010)
3 METHODOLOGY

3.1 Problem definition
The raw materials for biofuels being produced over large geographical areas have a limited availability window and often are handled as very voluminous materials. Thus, the transportation and logistics between the point of production and biorefinery becomes a vital part of the overall operational, economic and energetic viability of the biofuel production process. The necessary requirements include a reliable and optimized infrastructure capable of supplying biomass components to be fed into the biorefinery in the right quantity at the right time. In this regard, the supply chain must comprise optimized steps of harvesting biomass crops, collecting biomass residues, storing and transportation of biomass resources.

3.2 Objectives
The objectives of the study are to minimize the cost of biomass supply to a biorefinery, minimizing the impacts of entire system on environment along with maximizing the efficiency of the system by minimizing the energy consumption in different level of biomass logistics.

The level of decisions made by the model

Strategic decisions
- Acres (field-land) leased for biomass production
- Location and capacity of storage site(s)

Tactical decisions
- Acres of land cultivated
- Selection of harvesting/collecting method(s)
- Number of harvesting units required
- Number of collecting units required
- Number of transportation units required
- Allocation of harvest units to the biomass source site(s)
- Allocation of collecting units to the biomass source site(s)
- Allocation of transportation units to the in-field storage site(s)
• Allocation of transportation units to the storing site(s)
• Biomass harvesting schedule
• Biomass collecting schedule
• Biomass storing schedule
• Biomass transporting schedule

Operational decisions
• Amount of biomass harvested at each biomass source site(s)
• Amount of biomass collected at each biomass source site(s)
• Amount of biomass stored at sides of the field(s)
• Amount of biomass transported from storage site to biorefinery site(s)
• Amount of biomass transported from in-field storage site to biorefinery site(s)
• Number of required labor for harvesting, collecting, storing and transportation processes

Model assumptions
• The existing logistics assumes fixed quantitative of ready-to-deliver raw materials at each delivery point
• Demand from biorefinery is fixed and known for each month
• The network structure includes biomass source sites, in-field storage sites, Inventory sites and biorefinery sites.
• The location of biomass source site and biorefinery site are known.
• The harvesting units for agricultural biomass includes (self-propelled windrower, rake, large square baler, rake tractor, baler tractor, Self-propelled combine and forage harvester).
• The collecting unit includes (bale handler, automatic stinger stacker, silage wagon, forage wagon and tractors)
• The transportation unit includes (truck, semi-trailer truck and loader)
• The storage methods include ([In-field storage]: reusable tarp on crushed rock, [Inventory]: enclosed structure with crushed rock floor).
• The cost of pretreatment (drying) in Inventory site is known
• Weather condition and daylight hours determine the number of field operating work-hours available in a time period.

3.3 System definition
In this system, we considered several steps of biomass production includes: cultivation, harvesting, collecting, storage and transportation. Therefore, we are going to cultivate a certain amount of special type of biomass, harvesting and collecting the feedstocks, send them to the storage sites and after that transport biomasses from the inventory or in-field storage sites to the biorefinery based on the demand in each time period. Furthermore, there is a penalty cost regarding the moisture content of feedstocks which send to the biorefinery. If the moisture content of transferred biomass is more than that range which defined by biorefinery, then a penalty cost charged for that shipment.

In cultivation step, this study considers all members of the first and the second generations of bioethanol as sources of biomass. Moreover, three types of harvesting and collecting systems including baling, ensiling and chopping is considered in this work. For instance, the first generation of bioethanol consists of several biomass types such as corn, sugarcane, maize, molasses, sorghum and so on which can be harvested and collected by ensiling or chopping system. The second generation of bioethanol consists of many biomass types such as switchgrass, alfalfa, miscanthus, corn stover, wheat straw, rice straw and so on which can be harvested and collected by the baling system.

3.4 Biomass sources
If we consider Switchgrass as an entity into the system, it can be harvested by baling system. Therefore, by means of a windrower harvester, switchgrass is harvested and raked after drying in the field and then baled in to large square bales which are stored in storage locations until shipping to a central plant. Switchgrass can be baled into two forms of round or large square bales (Lewandowski, 2003). For the purposes of this study the bale size of (3ft. x 4ft. x 8ft) is considered for bailing system. When the baling is completed, the bales are distributed across the field by an automatic bale stinger and bale handler. These bales are loaded individually by a Loader onto a
truck with a semi-trailer, hauled to the storage location, and then unloaded into storage facilities. Thereafter, the stored biomass transferred into the biorefinery site based on the demand schedule. By considering corn as a source of biomass in the system, it can be harvested by either ensiling or chopping system. Therefore, if ensiling system is selected, we need a combine-harvester and silage wagons to gather feedstocks from the source site and transfer them to the storage sites and then, send them to the biorefinery according to the demand schedule. However, if Chopping system is opted, we can use a forage harvester with forage wagons in order to gather feedstocks from the field and then send them to the storage sites and after that, transport biomasses to the biorefinery based on the demand schedule.
4 MACHINE PERFORMANCE

The equipment considered in this study consists of self-propelled windrowers, rakes, large-square baler, and automatic stinger stacker with bale handler, tractors, combine-harvester, and silage wagons, forage-harvester, loafers (forage wagon), trucks and semi-trailer trucks. The harvest unit can be categorized into three groups: first, baling system which consists of a windrower, rake and large square baler. Second, ensiling system which consists of a combine-harvester and third, chopping system which consist of a forage-harvester.

The collecting units in the baling system consists of an automatic bale stacker with bale handler, the ensiling system includes silage wagons with tractors and chopping system consist of loafers with tractors. The transportation unit consists of trucks, semi-trailer truck and loaders. The characteristics for the units used in the model are described in the following paragraphs.

4.1 Effective Field Capacity (EFC)
The Effective Field Capacity is determined as the amount of material harvested per hour. The EFC of a machine is defined based on its operating width, average travel speed, and efficiency (Hanna M, 2002). The EFC of a harvest unit can be improved by matching the field capacities of all machines in the system (Kemmerer and Liu, 2012). The EFC value of a machine can be calculated by using the formulas number (1-2). All the information regarding operating width, speeds, and efficiencies for the machineries were gained from the ASABE standard D497.5 (Srivastava et al., 2006; ASABE.D497.5, 2006). Tables (3-5), presents the EFC of the harvesting equipment for this study.

\[
EFC_{\text{machine}} = TEOCAP_{\text{machine}} \times F_{E_{\text{machine}}}
\]  

\[
TEOCAP_{\text{machine}} = \left( \frac{SPD_{\text{machine}} \times MW_{D_{\text{machine}}}}{825} \right)
\]
### Table 3: EFC of harvesting units in baling system (Sharma, 2012)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Working Width (ft.)</th>
<th>Speed (mph)</th>
<th>Efficiency (%)</th>
<th>EFC (acres/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-propelled windrower</td>
<td>16</td>
<td>8</td>
<td>80</td>
<td>12.4</td>
</tr>
<tr>
<td>Rake</td>
<td>13</td>
<td>8</td>
<td>80</td>
<td>10.1</td>
</tr>
<tr>
<td>Large square baler</td>
<td>32</td>
<td>8</td>
<td>80</td>
<td>24.8</td>
</tr>
</tbody>
</table>

### Table 4: EFC of harvesting units in ensiling system (Hanna Mark, 2016)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Working Width (ft.)</th>
<th>Speed (mph)</th>
<th>Efficiency (%)</th>
<th>EFC (acres/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combine harvester</td>
<td>17.87</td>
<td>4.5</td>
<td>80</td>
<td>7.8</td>
</tr>
</tbody>
</table>

### Table 5: EFC of harvesting units in chopping system (Hanna Mark, 2016)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Working Width (ft.)</th>
<th>Speed (mph)</th>
<th>Efficiency (%)</th>
<th>EFC (acres/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forage harvester</td>
<td>20.62</td>
<td>15</td>
<td>80</td>
<td>30</td>
</tr>
</tbody>
</table>

4.2 Harvesting units

The harvest unit is a group of harvest machineries that work together. In this work, three harvesting units include baling, ensiling and chopping is selected for investigation. All required information regarding the harvesting and collecting activities costs is illustrated in the following table.

### Table 6: Harvesting and collecting activity costs (Kumar and Sokhansanj, 2007)

<table>
<thead>
<tr>
<th>System types</th>
<th>Harvesting activity cost ($/dry ton)</th>
<th>Collecting activity cost ($/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baling</td>
<td>10.8</td>
<td>24.1</td>
</tr>
<tr>
<td>Ensiling</td>
<td>8.2</td>
<td>22.63</td>
</tr>
<tr>
<td>Chopping</td>
<td>7.92</td>
<td>14.81</td>
</tr>
</tbody>
</table>

There is a certain amount of environmental impacts based on the selected harvesting method. Furthermore, each harvesting method consumes certain amount of energy and all the information regarding the energy consumption and environmental impacts can be found in the following table.

### Table 7: Energy consumption and GHG emission harvesting (Kumar and Sokhansanj, 2007)

<table>
<thead>
<tr>
<th>Harvesting systems</th>
<th>Total energy consumption (MJ/dry ton)</th>
<th>GHG emission(kg CO₂/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baling</td>
<td>39.5</td>
<td>3.07</td>
</tr>
<tr>
<td>Ensiling</td>
<td>145.68</td>
<td>110.3</td>
</tr>
<tr>
<td>Chopping</td>
<td>39.5</td>
<td>3.07</td>
</tr>
</tbody>
</table>

4.2.1 Baling system

Baling system as a harvesting method can be used in order to harvest and collect feedstocks in bale format. If we consider the baling system, the lowest material capacity is related to the baler
machine. Therefore, the capacity of other machines in this system should be harmonized with the capacity of the baler. The required number of machineries in baling unit can be defined by applying the equation (3). We should consider that the required number of balers can be calculated by the equation number (4). In this study, a harvest unit with an EFC of 25.21 was considered for baling system.

\[
N_{machine} = \text{ROUND}\left(\frac{EFC_{baler}}{EFC_{machine}}\right)
\]  

(3)

\[
N_{baler} = \text{ROUND}\left(\frac{EFC_{HUnit}}{EFC_{baler}}\right)
\]  

(4)

Furthermore, we should consider that based on harvesting and collecting method which selected in the system, there is certain amount of environmental impact and energy consumption regarding that method. The required information regarding these measures presented in the following table.

<table>
<thead>
<tr>
<th>Baling system (Square bale)</th>
<th>Energy Consumption (MJ/dry ton)</th>
<th>GHG emission (kg CO2/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>48.6</td>
<td>131.7</td>
</tr>
<tr>
<td>Harvesting</td>
<td>37.7</td>
<td>3.4</td>
</tr>
<tr>
<td>Collecting</td>
<td>115.9</td>
<td>10.6</td>
</tr>
<tr>
<td>Storage</td>
<td>10.7</td>
<td>1</td>
</tr>
</tbody>
</table>

**Windrower**

Switchgrass as a source of biomass can be harvested by means of typical hay equipment (Christensen, 2010). In order to harvesting switchgrass in this study, a 16ft. self-propelled windrower was presumed to be used. Based on this type of windrower, the working output capacity is around 48 (dry tons per hour). As a feature of this windrower, driver is able to change the speed of the machine according to the various yield conditions to gain the working output capacity (Herron, 2012) for instance, the operator can reduce speed of the machine if the yield of biomass is high and increase the speed if the yield of biomass is low. Adjusted speed for windrower machine can be assessed by the following formula (Sokhansanj et al., 2008):
\[ S = S_b \times \left( \frac{Y_b}{Y} \right) \]  

Where;  
\( S = \) Adjusted speed (mph)  
\( S_b = \) Optimum speed for the optimum yield mph  
\( Y_b = \) Optimum yield (tons/acre)  
\( Y = \) Yield (tons/acre)

**Rake**

A rake is the main tool used to move cut material into windrows and to simplify the baling operation and decreases biomass moisture content (Cheng, 2010). In this study, a 13ft. finger wheel rake powered by a 75 HP (standing for horse power) tractor was considered. This model of rake machine has a 3 (dry ton/hour) working output capacity (Herron, 2012).

**Baler**

Baler, as a standard harvesting machine, is used by farmers in order to make bales. Various size of bales can be produced by baler machine. The information regarding the characteristics of common sizes of bale is showed in the table (9). In this study, we assumed that bales were made in large square shape with the size of (3ft. x 4ft. x 8ft.). Many researchers have found that square bales are a more effective form of storage than round bales as they are easier to handle, more durable when handled, more economical, and easier to transport (Thorsell et al., 2004; Larson et al., 2010). In this study, 21 (dry tons per hour) considered as working output capacity for large square baler (Herron, 2012). The speed adjustment for baler was done using the equation number (5) with the same procedure as for the windrower speed adjustment.

<table>
<thead>
<tr>
<th>Bale size (ft.)</th>
<th>Bale weight (ton)</th>
<th>Bale volume (ft(^3))</th>
<th>Bales per load</th>
<th>Total Payload</th>
<th>Load layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>3ft x 4ft x 8ft</td>
<td>0.54</td>
<td>96</td>
<td>39</td>
<td>20.98</td>
<td>1W,3H,13L</td>
</tr>
<tr>
<td>4ft x 4ft x 8ft</td>
<td>0.72</td>
<td>128</td>
<td>26</td>
<td>18.65</td>
<td>1W,2H,13L</td>
</tr>
</tbody>
</table>

*W(width), H(height), L(length)

*Assumes the density of 11.21 (lb./ft\(^3\)) for all bales
4.2.2 Ensiling system

Ensiling system as a harvesting method is used for wet biomasses. If we consider an ensiling unit for harvesting, it includes machineries such as combine harvester and silage wagons. In this work, a harvesting unit with an EFC value 8 is considered for ensiling system.

**Combine-harvester**

Combine-harvester is a kind of standard farm machines that used for harvesting grain crops. The advantage of using combine-harvester is that we can accomplish three different processes such as reaping, threshing and winnowing into a single process. Therefore, combine harvester as a labor saving development which is very important from the economical aspect and this machine can significantly reduce the requirement of workers that must be involved in agricultural works (Lienhard, 2004). The required number of combine harvesters in a harvesting unit can be determined by the equation number (6).

\[
N_{combine} = ROUND\left(\frac{EFC_{Unit}}{EFC_{combine}}\right)
\]  \hspace{1cm} (6)

In this study, a self-propelled combine-harvester with operating power 92 (KW), consists of 3 rows and snapper head with size of 1.5 which has a working width of 5.5 m, working speed 4.5 (mph) and efficiency %80 was selected (Guide to machinery costs, 2013). All the information regarding this type of machine can be found in the table (10).

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>Average purchase price ($)</th>
<th>Salvage value ($)</th>
<th>Average investment ($)</th>
<th>Depreciation ($/hr)</th>
<th>License &amp; insurance ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combine 92(kw), 3rows,1.5(m) snapper</td>
<td>122614</td>
<td>12261</td>
<td>67438</td>
<td>2759</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td>Interest ($/hr)</td>
<td>Fixed cost ($/year)</td>
<td>Repair and maintenance ($/hr)</td>
<td>Fuel Cost ($/hr)</td>
<td>Variable cost ($/hr)</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>40800</td>
<td>12</td>
<td>16</td>
<td>28</td>
</tr>
</tbody>
</table>
4.2.3 Chopping system

In this work a chopping system was considered for harvesting dry biomasses from farm. The harvesting chopping unit consists of machineries such as forage harvester and forage wagons. For the purpose of this study, a chopping harvest unit with an EFC value 31 was considered.

**Forage harvester**

A forage-harvester is a kind of standard farm machines that is used for making silage by harvesting forage plants to make silage. This machine gathers crop materials from the field and then chopped them into small pieces and after that stores the feedstocks into a bin or wagon (forage wagon). Usually, there are two types of forage harvester machines, self-propelled or pulled by tractor. Forage harvesters are commonly equipped by a blower which helps to transfer cut crops to a wagon dragged behind or alongside the harvester to gather the materials (Priepke, E.H. and Wagstaff, R.A, 1980). The required number of forage harvester machine in the unit can be calculated by the equation (7).

\[
N_{\text{forage harvester}} = \text{ROUND}\left( \frac{EFC_{\text{Unit}}}{EFC_{\text{forage harvester}}} \right)
\]  

(7)

A self- propelled forage harvester with 2 harvester rows was selected for this study. All the information regarding this type of machine can be found in the table (11).

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>Average purchase price ($)</th>
<th>Salvage value ($)</th>
<th>Average use per annum (hr)</th>
<th>Depreciation ($/hr)</th>
<th>Average investment ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forage harvester 2row</td>
<td>30714</td>
<td>3071</td>
<td>200</td>
<td>14</td>
<td>16892</td>
</tr>
</tbody>
</table>

Table 11: Fixed cost and variable cost Forage harvester (Guide to machinery costs, 2013)

<table>
<thead>
<tr>
<th>Interest ($/hr)</th>
<th>Fixed cost ($/year)</th>
<th>Repair and maintenance ($/hr)</th>
<th>Variable cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4453</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

4.3 Collecting units

Collecting unit refers to the group of machineries which operates together in order to gather the feedstocks from the source site. Based on the harvesting system, we can select a proper collecting
system for accumulating the crops from a field. Furthermore, the information regarding the energy consumption and GHG emission by the different collecting units is depicted in the following table.

Table 12: Energy consumption and GHG emission collecting (Kumar and Sokhansanj, 2007)

<table>
<thead>
<tr>
<th>Collecting systems</th>
<th>Total energy consumption (MJ/dry ton)</th>
<th>GHG emission (kg CO$_2$/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baling</td>
<td>200.43</td>
<td>15.55</td>
</tr>
<tr>
<td>Ensiling</td>
<td>211.01</td>
<td>16.37</td>
</tr>
<tr>
<td>Chopping</td>
<td>217.69</td>
<td>16.89</td>
</tr>
</tbody>
</table>

4.3.1 Baling system

In the baling system, produced bales by a baler can be transferred from the source site to the side of the field by using a bale stacker and bale handler.

**Bale stacker and bale handler**

Bale stacker as a standard type of farm machineries can be used for collecting, transporting, and stacking bales at the side of a field. In this study, we consider an automatic Stinger Stacker 6500 which is able to handle 12 bales per each load. The capacity of this machine in the normal harvesting condition is about 80 to 120 bales per hour (in-field transport) (Stingerltd.com, 2011; Stinger stacker 6500, 2011). To load and unload bales onto trucks we need to use a bale handler. The forks are designed to pick-up the bales without damaging them. The information regarding this type of machine is demonstrated in the following tables (13-14).

Table 13: Specifications of automatic stinger stacker

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>loading time (hr/per bale)</th>
<th>Unloading time (hr/per bale)</th>
<th>loading mass (per load)</th>
<th>Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic stinger stacker</td>
<td>0.004</td>
<td>0.002</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 14: Bale stacker and bale handler costs (Sharma, B., 2012)

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>Retail price ($)</th>
<th>Purchase price ($)</th>
<th>Fixed cost ($/year)</th>
<th>Variable cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stinger stacker 6500</td>
<td>145992</td>
<td>124093</td>
<td>22882</td>
<td>114</td>
</tr>
<tr>
<td>Bale handler</td>
<td>94000</td>
<td>79000</td>
<td>14549</td>
<td>46</td>
</tr>
</tbody>
</table>

4.3.2 Ensiling system

In the ensiling system, harvested feedstocks can be collected by using the silage wagons. In order to operating these wagons, we need a tractor for each of them.
**Silage wagon**

Silage wagon or silage box, is a kind of wagon that operates with the power of tractor to pull it. This machine used for gathering silages from the field. The capacity of silage wagon depends on its volume (Rowan et al., 1982). In this study, a silage wagon with the capacity of 10-tons was considered. To be able to operate, this wagon needs a 75 HP tractor. All the information regarding the specifications of these machines can be found in the tables (15).

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>HP</th>
<th>Capacity dry ton (m³)</th>
<th>Efficiency</th>
<th>loading time (min)</th>
<th>Unloading time (min)</th>
<th>Fixed Cost ($/hr)</th>
<th>Variable Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silage wagon</td>
<td>120</td>
<td>34</td>
<td>0.9</td>
<td>4</td>
<td>2</td>
<td>12.08</td>
<td>11.46</td>
</tr>
<tr>
<td>Forage wagon</td>
<td>80</td>
<td>30</td>
<td>0.85</td>
<td>0.5</td>
<td>0.25</td>
<td>20.38</td>
<td>6.09</td>
</tr>
</tbody>
</table>

4.3.3 Chopping system

The chopping system for collecting includes machineries such as forage wagons or loafers and tractors which is required for operating the forage wagons.

**Forage wagon**

In this system, a forage harvester picks up the dry biomass from windrower and chops it into smaller pieces (2.5-5cm). The chopped biomass is blown into a forage wagon traveling along side of the forage-harvester. Once filled, the forage wagon is pulled to the side of the farm and unloaded (Van, 1958). In this study, a forage wagon with the capacity of 10-tonnes biomass was considered. The forage wagon also needs a tractor for operation, then a 75 (hp.) tractor considered in this study as forage tractor. The required information regarding the forage wagon and forage tractor can be found in the following table.
Table 16: Silage and forage tractors costs elements (Guide to machinery costs, 2013)

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>purchase price ($)</th>
<th>Salvage value ($)</th>
<th>Average investment ($)</th>
<th>Depreciation ($/hr)</th>
<th>License and insurance ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Silage tractor</td>
<td>37156</td>
<td>3716</td>
<td>20436</td>
<td>2.79</td>
<td>0.36</td>
</tr>
<tr>
<td>**Forage tractor</td>
<td>37156</td>
<td>3716</td>
<td>20436</td>
<td>2.79</td>
<td>0.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interest ($/hr)</th>
<th>Fixed cost ($/year)</th>
<th>Repair and maintenance ($/hr)</th>
<th>Fuel cost ($/hr)</th>
<th>Variable cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Silage tractor</td>
<td>1.74</td>
<td>4.88</td>
<td>3.72</td>
<td>12.9</td>
</tr>
<tr>
<td>**Forage tractor</td>
<td>1.74</td>
<td>4.88</td>
<td>3.72</td>
<td>11.29</td>
</tr>
</tbody>
</table>

*Silage tractor (High power demand, 74KW)
**Forage tractor (medium power demand, 74KW)

4.4 Storage

Storage of biomass in a supply chain includes all processes accompanying with stacking, silage, piling and protecting the biomass from severe environmental conditions in order to send raw materials in a good condition to biorefinery (Hess et al., 2009). There are several options to protect stored biomass and minimize compositional changes during storage. It could be possible to store them either protected or unprotected, on crushed rocks or on ground unless they are kept in an inside storage facility. The best storage method is determined by considering storage cost, length of storage period, biomass losses that is prevented during storage and weather conditions in the region of storage (Miranowski, 2010).

4.4.1 Covered Inventory

In this method, feedstocks can be stored in an inventory site with covered structure. The floor of the inventory could be covered with crushed rocks or other types of materials could be used such as pallets in order to store biomasses. In this type of storage, it could be possible to use a dryer to control the moisture content of feedstocks. For this study, we consider that biomass is protected with a covered structure on the crushed rock. All the required information related to this type of storage is presented in the table (18). Furthermore, based on the percentage of moisture content of feedstocks, we used a pretreatment method (drying) in this type of storage. The information regarding pretreatment (drying) process can be found in the following table.
4.4.2 In-field storage

At in-field storage site, feedstocks are stored on a base of crushed rock without any cover. The storage period in comparison with inventory site is much longer because in this type of storage we are going to dry biomass by a natural procedure with air. In this method, the risks related to biomass loss and unforeseen weather condition should be considered. However, the storing costs related to this method is much lower than the covered storage. The required data regarding this type of storage is demonstrated in the following table.

### Table 18: Inventory and in-field storage information

<table>
<thead>
<tr>
<th>Storage types</th>
<th>Storing method</th>
<th>Area storage site (m²)</th>
<th>capacity storage site (ton)</th>
<th>Price construction ($/m²)</th>
<th>CRF structure</th>
<th>variable cost storage ($/ton)</th>
<th>Moisture content (%)</th>
<th>Dry matter loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory</td>
<td>enclosed structure with crushed rock floor</td>
<td>1500</td>
<td>86</td>
<td>0.12</td>
<td>13</td>
<td>15</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>In-field storage</td>
<td>reusable tarp on crushed rock</td>
<td>400</td>
<td>795</td>
<td>2.7</td>
<td>0.19</td>
<td>3</td>
<td>25</td>
<td>3</td>
</tr>
</tbody>
</table>

4.5 Transportation

It was assumed that a 24-ton truck and a 52 ft. semi-trailer truck should be used for transportation of the biomass to the biorefinery. Since the distances calculated were direct distances, a circuitry factor was multiplied to provide a better estimate of actual distances. The circuitry factors for suburban and rural areas are 1.3 and 1.14, respectively (Kuei, 2000). For the present study, a circuitry factor of 1.14 was used. All the required data related to transportation methods can be found in the tables (19, 23-24).
Table 19: Energy consumption and GHG emission Transportation Units (Kumar and Sokhansanj, 2007)

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>Total energy consumption (MJ/dry ton)</th>
<th>GHG emission(kg CO2/dry ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-trailer truck</td>
<td>1026.75</td>
<td>79.68</td>
</tr>
<tr>
<td>Pile or Silage truck</td>
<td>1056.5</td>
<td>81.98</td>
</tr>
</tbody>
</table>

4.6 Available work hours

The available time for performing agricultural operations like soil preparation, cultivation and harvesting can be limited and affected by weather conditions (Baier, 1973). To make a decision for machinery, it is very important to have a good estimation of available work hours (Rounsevell and Jones, 1993). The methodology in this model was developed to estimate harvesting/collecting work-hours by considering weather parameters such as rainfall, snow, temperature, and wind speed. Growing and harvesting/collecting weather defined by the weather conditions during the growing and harvesting months and it could be favorable (F) or in favorable (INF). The following table illustrates the overall weather scenarios and related factors with certain amount of probabilities regarding each scenarios.

Table 20: Weather scenarios with probabilities

<table>
<thead>
<tr>
<th>Overall weather scenarios</th>
<th>Growing season</th>
<th>Harvesting/collecting season</th>
<th>Production conversion factor</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>condition</td>
<td>Factor $\phi$</td>
<td>Factor $\sigma$</td>
<td>$\varphi$</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>1.0</td>
<td>F</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>1.0</td>
<td>INF</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>INF</td>
<td>0.95</td>
<td>F</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>INF</td>
<td>0.95</td>
<td>INF</td>
<td>0.9</td>
</tr>
</tbody>
</table>

4.6.1 Time available for field operations

The work hours available per day were calculated using Daylight Hours Explorer software (daylight Hours Explorer, 2010). Table (21) shows the daylight hours and available field operation hours in each time periods. The available field operation (e.g. harvesting, collecting) hours were assumed to be on %80 of the daylight hours. Twenty percent of the field operation hours were
assumed to be lost due to the machinery breakdown, unavailability of labor, and unforeseen events. Furthermore, in this study, a yield adjustment factor is considered which varies between 0 and 1 and adjusts the change in yield of biomass with the harvest time periods.

Table 21: Time available for field operations

<table>
<thead>
<tr>
<th>Time period (t)</th>
<th>Months</th>
<th>YADJ</th>
<th>Daylight hours (hr)</th>
<th>Available field operation hours (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jan.</td>
<td>0.98</td>
<td>7.5</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Feb.</td>
<td>0.96</td>
<td>9.5</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Mar.</td>
<td>0.92</td>
<td>11.5</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Apr.</td>
<td>0.97</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>May</td>
<td>0.91</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Jun</td>
<td>0.98</td>
<td>17.5</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>July</td>
<td>0.93</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>8</td>
<td>Aug.</td>
<td>0.97</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>Sep.</td>
<td>0.92</td>
<td>12.5</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>Oct.</td>
<td>0.94</td>
<td>10.5</td>
<td>8</td>
</tr>
<tr>
<td>11</td>
<td>Nov.</td>
<td>0.96</td>
<td>8.5</td>
<td>7</td>
</tr>
<tr>
<td>12</td>
<td>Dec.</td>
<td>0.98</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

4.7 Economics

In this study, to calculate the total cost of machineries, the cost was divided into two categories, namely fixed and variable costs (Guide to machinery costs, 2013). The proposed model considers harvesting, collecting, transportation, and storage costs.

4.7.1 Fixed costs

Fixed costs are associated with equipment ownership and does not change with the level of usage. Fixed costs per hour of usage are inversely proportional to the extent of annual usage (Guide to machinery costs, 2013).
**Depreciation**

Depreciation is related to the reduction in value of an equipment during the life cycle of that equipment which is the result of wear, obsolescences, and age of machine (Guide to machinery costs, 2013). The depreciation was calculated by using the following formula (ASABE. D497.5, 2006):

\[
R = \left[ P - \frac{S}{(1+i)^n} \right] \times \frac{(1+i)^n}{(1+i)^n-1} + (P \times K) + \left( \frac{-S_i}{(1+i)^n} \right) \tag{8}
\]

Where,
- \( R \) = Annual fixed cost ($/year)
- \( P \) = Purchase price of equipment ($)
- \( S \) = Salvage value for the equipment ($)
- \( I \) = Annual interest rate (fraction)
- \( n \) = Useful life of equipment (years)
- \( k \) = Rate of taxes, housing, insurance (fraction)

**4.7.2 Variable costs**

It is possible to identify five main variable cost components regarding the supply of biomass to the biorefinery as biomass, harvest, collection, storage, and transportation (EERE, 2011). In this study, the growing cost related to the different farm activities such as planting, fertilizing, and so on is termed as cost of biomass production which is about 18.5 ($/ton). Furthermore, variable costs related to the different harvesting and collecting activities were considered in the study. The variable cost for the equipment depends on the use of machinery and is comprised of repairs and maintenance (R&M), fuel and lubrication, and labor. The R&M cost is a key component of variable cost and increases with the use of equipment. As the machine ages, it tends to become the largest cost component of owning and operating farm machinery (Bakht et al., 2008). The cost of repair and maintenance can be assessed by the following equation (Turhollow et al., 2009):

\[
Cr_{m_{hourly}} = \frac{Cr_{m_{life}} \times LP}{h} \tag{9}
\]

Where,
- \( Cr_{m_{hourly}} \) = Average R&M cost ($/hr)
- \( Cr_{m_{life}} \) = Lifetime R&M cost (fraction of current list price)
\[ LP = \text{List price of equipment} \]
\[ h = \text{Useful life of equipment (hr)} \]

In this study, the work rates is obtained from the USDA-NASS (USDA-NASS, 2007). The value of working hours determined twenty percent higher than machine hours plus a thirty percent marginal benefits rate. Furthermore, the cost of machine lubrication was determined fifteen percent of the fuel cost (Turhollow et al., 2009). In this study, the following formulas (10-11) was considered for calculation of fuel consumption (Sharma, 2012):

\[ FU = F_{PTO} \times (Load \times PTO) \] (10)

\[ F_{PTO} = 0.52 \times Load + 0.77 - (0.04 \times \sqrt{738 \times Load + 173}) \] (11)

Where, \( FU = \text{Fuel used (gallons/hr)} \)
\( Load = \text{Average percent of needed horsepower} \)
\( PTO = \text{Power take - off (hp)} \)
\( F_{PTO} = \text{Typical fuel use for a specific operation (gal/hp/hr)} \)

In the following table, all the required information regarding the fixed and variable costs of baling system is presented.

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>Windrower</th>
<th>Large square baler</th>
<th>Baler tractor (200 hp)</th>
<th>Rake</th>
<th>Rake tractor (75 hp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retail price ($)</td>
<td>149309</td>
<td>120560</td>
<td>202899</td>
<td>4700</td>
<td>60666</td>
</tr>
<tr>
<td>Purchase price ($)</td>
<td>126913</td>
<td>102476</td>
<td>172464</td>
<td>3994</td>
<td>51566</td>
</tr>
<tr>
<td>Fixed cost ($/year)</td>
<td>47196</td>
<td>53066</td>
<td></td>
<td></td>
<td>11904</td>
</tr>
<tr>
<td>Variable cost ($/hr.)</td>
<td>93</td>
<td>114</td>
<td></td>
<td></td>
<td>43</td>
</tr>
</tbody>
</table>

The capital recovery method was considered in order to determine the costs related to biomass storage. Furthermore, in order to simplify the calculation, zero value considered for salvage cost of all storage constructions. The following formulas demonstrates how the capital recovery factor was calculated (Soi.wide.ad.jp, 2017).
\[ CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \]  

(12)

\[ Cap = P \times CRF \]  

(13)

Where,  

- \( CRF \) = Capital recover factor (fraction)
- \( Cap \) = Annual capital cost ($/year)
- \( P \) = Purchase price ($)
- \( i \) = Interest rate (fraction)
- \( n \) = Life of investment (years)

In order to determine the cost of transportation units, it was presumed that the working hours per day is equal to 10. To estimate the number of trips we need to determine the travel cycle time. The time required for loading 36 bales into the truck is 30 minutes. The same amount of time used for unloading that quantity of bales from the truck. The cycle time is the sum of loading, travel and unloading time. For instance, if the travel time (time to travel to the Plant and return) is 1 hour, then the cycle time is 1 hour (travel) + 0.5 hour (loading) + 0.5 hour (unloading) = 2 hours. In an uninterrupted 10 hours’ day, an individual truck might make 5 trips. Table 23 presents the value of parameters assumed to calculate the variable costs of transportation.

Table 23: Specifications of transportation units (Guidelines on maximum weights and dimensions of mechanically propelled vehicles and trailers, including maneuverability criteria, 2017)

<table>
<thead>
<tr>
<th>Machinery Type</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Weight Capacity (ton)</th>
<th>Volume Capacity (m³)</th>
<th>Speed (km/hr)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-trailer truck</td>
<td>16.1</td>
<td>2.5</td>
<td>-</td>
<td>30</td>
<td>95</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>Pile-Silage Truck</td>
<td>12</td>
<td>2.5</td>
<td>3</td>
<td>25</td>
<td>90</td>
<td>80</td>
<td>75</td>
</tr>
</tbody>
</table>

Moreover, all the required data in order to calculate the fixed and variable cost of transportation units are presented in the following table.
Table 24: Fixed cost and variable cost of transportation units (Guide to machinery costs, 2013)

<table>
<thead>
<tr>
<th>Machinery type</th>
<th>purchase price ($)</th>
<th>Fuel usage (L/100km)</th>
<th>Average investment ($)</th>
<th>Depreciation ($/Km)</th>
<th>Insurance ($/Km)</th>
<th>License ($/Km)</th>
<th>Interest ($/Km)</th>
<th>Fixed cost ($/Km)</th>
<th>Repair and maintenance ($/Km)</th>
<th>Fuel Cost ($/Km)</th>
<th>Oil ($/Km)</th>
<th>Variable cost ($/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Pile or Silage truck</td>
<td>75847</td>
<td>46</td>
<td>41716</td>
<td>9.75</td>
<td>2.4</td>
<td>0.47</td>
<td>5.1</td>
<td>0.18</td>
<td>5.2</td>
<td>44.56</td>
<td>2</td>
<td>0.64</td>
</tr>
<tr>
<td>**Semi-trailer truck</td>
<td>88695</td>
<td>45</td>
<td>48782</td>
<td>11.4</td>
<td>2.8</td>
<td>0.48</td>
<td>5.9</td>
<td>0.21</td>
<td>6.1</td>
<td>43.59</td>
<td>1.95</td>
<td>0.67</td>
</tr>
</tbody>
</table>

*Dual axle, 22 ton, axor
**Single differential, 18 ton, axor
5 OPTIMIZATION AND SIMULATION METHODS

Bioenergy as a green energy source is very momentous for the future of energy production. Based on the research by You et al., (2012) efficient modeling and optimization approach can figure out and detect the sustainable solutions for design and operation of BSCs and decrease the negative effects regarding the bioenergy.

Modeling and simulations are commonly applied in logistics analysis due to complexity in the estimation of logistical costs and energy usage. Simulation methods can provide a better design of the logistical network and figure out the dimensions of this network. However, optimization model can determine the optimal design of the logistics network through related constraints such as resource sites, transportation structures and energy mills. The classification of resource positions, collection sites, transshipments sites, pre-treatment sites and conversion sites are required to model the logistics and supply networks of biomasses (Sharma et al., 2013). Figure 9 demonstrates the quantitative performance of the system that defined in this study.

5.1 Supply chain modeling
There are four types of supply chain models: Stochastic Model (SP), Deterministic Model (DM), Hybrid Model (HYB) and IT-Driven Model (ITDM). It is possible to classify the deterministic model into two types: single objective and multiple objectives. If we consider the single objective model, typically there are two approaches in this field: Linear programming (Mixed integer/Integer linear programming) and Nonlinear programming (Mixed integer/Integer nonlinear programming). A similar condition exists if we consider the multiple-objective model. (Sharma et al., 2013).
5.2 Modeling approach

Based on the reviewed literature, most of the models concentrate on strategic decisions of BSC such as location and capacity of biorefinery as well as the size of plants. They also focus on the tactical and operational decisions of BSC such as material flow and inventory of feedstocks (Dal-Mas et al., 2011). Figure 10 illustrates the modeling approach which applied in this study.

Sustainability, cost and uncertainty are three key factors that should be considered in modeling approach. Moreover, there are six essential elements which are effective on the previously mentioned factors, namely, technology, social perception, biomass conversion, energy services, and scale of plant and market penetration. Biomass as an element in the biorefinery process has several important properties such as biomass type, seasonal availability, sustainable resource, uniform and continuous supply, energy crop management, harvesting and collection method, topographical constraints, biodiversity and ecology, supply contracts and policies.

Transportation as another element of BSCs has different characteristics such as mode of transportation, transportation infrastructure, transportation laws, environmental impacts, social impacts, local, regional, long distance. In addition, storage is also an important element of each BSCs which has some related properties such as storage system, location of storage sites, storage capacity, storage losses, storage duration, and storage risks and ensure continuous supply of feedstock.
Finally, pre-treatment is another key factor in BSCs which has several prominent characteristics such as technique, biorefinery requirement, and the location of pretreatment in the supply system and enhancing biomass attributes (Sharma et al., 2013).

![Figure 10. Modeling approach](image)

5.3 Modeling under uncertainties

Various sources of uncertainties exist in every BSCs such as biomass supply, weather condition, biomass yield, variation in demand, biofuel price and so on. To deal with uncertainties, researchers usually use the “Wait-and-see”, an approach that analyzes the present scenarios. In this approach, the researcher should hesitate and check the real random occurrence to decide based on the situation (Chen et al., 2011).

Scenario optimization, robust optimization and simulation optimization are examples of methods that can handle the uncertainties of biomass supply chain. It is important to know that the first and the second methods are limited to deal with a small group of scenarios. However, the simulation optimization approach provides a fast and non-disruptive assessing of many scenarios. This
approach combines both the simulation and optimization techniques to solve the BSC complexity issues. Basically, cost minimization and revenue maximization are the common objectives of these models but the main goal is to maximize the total supply chain surplus (Better et al., 2008). Uncertainties can be generally classified into two groups according to the multi-scale decisions: uncertainties in strategic or tactical levels which can be handled by optimizing approaches (Lee, 2012).
6 Model development

6.1 Model
A model is a mathematical description of a real-world problem and is a crucial part of modeling and optimization processes. It is sometimes too difficult and impossible to model all features of a problem because of too much complexity related to the dynamic environment of the problem. Therefore, scientists always try to model either a simplified form of the problem or prepare several expectations and approximations (Sarker and Newton, 2008).

6.1.1 Mathematical model
Mathematical model can generally be described by following formula (Sarker and Newton, 2008):

\[
\text{Maximize } f(x) \\
\text{Subjected to: } \quad g_i(x) \leq gb_i, \quad i = 1, \ldots, m \\
\quad h_j(x) = hb_j, \quad j = 1, \ldots, p \\
\quad x \geq 0
\]

where the objective function \( f \) is a function of a single variable \( x \), and the constraints \( g_i \) and \( h_j \) are general functions of the variable \( x \), \( gb_i \) and \( hb_j \), are the known constants for deterministic problems. The non-negativity constraint \( x \geq 0 \) is necessary for many practical problems (since many variables cannot be negative) and for many solution approaches (assumed by default) (Sarker and Newton, 2008).

6.2 Classification of Optimization problems
Optimization refers to the process of maximization or minimization of the problems. In optimization problems, the main purpose is to optimize the objective function which is a mathematical function that includes some variables. From the number of objectives point of view, optimization problems can be classified into two types: Single or multi-objective problems. Based on the nature of the problem, the included variable could be integer or real or a mix of both. Furthermore, depends on the order of the objective function, it could be linear or nonlinear (Sarker...
6.2.1 Deterministic VS. Stochastic approach
Deterministic approach refers to the type of mathematical modeling in which results are surly determined based on the relations among variables without any random variation. In deterministic models, a given input will always make the same output. However, in stochastic models, there are ranges of values for variables in the form of probability distributions (Sarker and Newton, 2008).

6.3 Model definition
According to the purpose of this study, a mathematical model formulated which can be able to find the optimum value for the three objective functions. In the first objective function which relates to the minimization of logistics costs of biomass, all the cost elements related to deferent processes of biomass production was considered in the model to reach the more precise results. The second objective function, provides the method to assess the amount of environmental impacts made by different processes of biomass logistics. Finally, the last objective function, calculates the maximum amount of efficiency for the system by minimizing the energy consumption in different
steps of biomass production. At the end, all three objective functions solve together to find the optimal solution which satisfy each objective function.

Based on the reviewed literature, there is lots of researches that focus on the topic of biomass logistics and supply chains. Information from previous works used in order to development of the model in this study.

Based on the biomass selection, the model suggests the best method for harvesting, collecting and transportation systems. If corn considered as a source of biomass in the system, from first generation of bioethanol group, then the proper method for harvesting and collecting is ensiling system and we should use ensiling trucks for transportation. However, if switchgrass considered as a source of biomass in the system, from second generation of bioethanol group, then the best method for harvesting and collecting is baling system and the proper transportation vehicle is truck with semi-trailer. The following figure shows the total structure of the model used in this work.
6.3.1 Network structure

The network structure includes biomass source sites, in-field storage sites, Inventory sites and biorefinery sites. The figure 13 illustrate the different parts of biomass logistics and the flow of materials in the system.

Figure 13: Schematic view of overall system
6.3.2 Limitations of the model

**Supply constraints**
- The total acres of biomass harvested must not exceed the total acres contracted for biomass cultivation in each biomass source site and time period.
- The total biomass harvested could be equal to the total tonnage procured by the biorefinery (In this study, the yield adjustment factor varies between 0 and 1 and adjusts the change in yield of biomass with the harvest time periods).

**Demand constraints**
The demand for biomass in the model was known and fixed, and the model worked towards meeting the demand along with minimizing cost of biomass supply to the biorefinery.

**Capacity constraints**
The total quantity of biomass harvested at the source site is constrained by the harvest work-hours available and the capacity of the harvest unit.

**Logical constraints**
Non-negativity restrictions on the decision variables.

6.3.3 Decision variables of the model
- The acres of field \(i\) leased for cultivation (\(acre \ lease_i\))
- The quantity of biomass transported from source site \(i\) to Inventory \(j\) and then transferred to the biorefinery site \(r\), at time period \(t\) (\(TBTSIR_{ijr,t}\))
- The quantity of biomass transported from source site \(i\) to in field storage site \(f\) and then transferred to the biorefinery site \(r\), at time period \(t\) (\(TBTSFR_{ifr,t}\))
- The location and distance of storage site \(j\) from biorefinery \(r\) (\(D_{jr}\))
- The tonnage capacity of storage site \(j\) (\(Cap_I_j\))

6.3.4 Binary variables
- Selection of harvesting methods \((H_e)\) \{1: if harvest method \(e\) selected, 0: otherwise\}
• Selection of collecting methods \((C_m)\) \{1: if collecting method \(m\) selected, 0: otherwise\}

• Selection of transportation method \((TRN_p)\) \{1: if transportation method \(p\) selected, 0: otherwise\}

6.3.5 Parameters

**Production**

• \(CP_{roduct}\): unit cost of planting, growing and farm costs

• \(Acrelease_i\): acre of land \(i\) leased for cultivation

• \(PP_i\): proportion of field \(i\) under cultivation

• \(ALC_i\): acre of field \(i\) cultivated

**Harvesting**

• \(FC_e\): fixed cost harvesting method \(e\)

• \(FC_{machines}\): annual fixed cost machine ($/year)

• \(Nmachines\): number of harvesting machines

• \(EFC_{machine}\): effective field capacity of machine

• \(TEOCAP_{machine}\): theoretical capacity of harvesting machines

• \(FE_{machine}\): field efficiency of harvesting machines

• \(MWD_{machine}\): operating width (e.g. cut width) of machine

• \(SPD_{machine}\): speed of harvesting machine

• \(HVcost_e\): variable cost of harvesting method \(e\) ($/hr)

• \(VCH_e\): variable cost of machines in harvesting method \(e\) ($/hr)

• \(VC_{machines}\): variable cost of machine ($/hr)

• \(EFC^*_{Hunit}\): field efficiency of harvesting unit

• \(NAHWH_t\): number of available harvesting working hours (hr)

• \(TBH_i_t\): tons of biomass harvested from source site \(i\) at time period \(t\)

• \(YIELD_i\): Yield of biomass at field \(i\) (tons/acre)

• \(PP1_i_t\): proportion of field \(i\) that should be harvested at time period \(t\)

• \(YADJ_t\): yield adjustment factor at time period \(t\)
Collecting

- $FC_m$: fixed cost machines in collecting method $m$
- $VC_m$: variable cost machines in Collecting method $m$
- $TBC_{it}$: tons of biomass collected from field $i$ at time period $t$
- $VCost_m$: variable cost collecting activity method $m$
- $\mu_{baler}$: average dry matter loss (DML) percentage in baling
- $BaleMass$: mass of each bale (ton/bale)
- $LT_{stinger}$: loading time of each bale onto stinger (hr/bale)
- $ULT_{stinger}$: unloading time of each bale from stinger (hr/bale)
- $D$: distance between farm $i$ and in-field storage site $f$ (km)
- $S_{stinger}$: average speed of stinger (km/hr)
- $LM_{stinger}$: mass of bales loaded onto stinger (ton)
- $Cost_{stinger}$: custom cost of stinger stacker ($/hr$)
- $NACWH_t$: the number of available collecting working hours (hr)

Inventory

- $OCI_{js}$: ownership cost of storage facility $j$
- $CRFStructure$: Capital recover factor storage facility (decimal)
- $PStructure_j$: cost storage $j$
- $PriceSI_j$: price structure inventory $j$ ($/m^2$)
- $AreaI_j$: the area of Inventory $j$
- $i$: Annual interest rate (decimal) = 8%
- $n$: Useful life of equipment (year) = 15
- $VCS_j$: variable cost storage in inventory $j$
- $PSI_{ts}$: period storage in inventory $j$
- $Cost_{drying}$: drying cost ($/ton$)
- $EVRate$: evaporation rate dryer
- $Gflow$: gas flow of dryer
**In-field storage**
- \(PriceINF\): the construction cost of in-field storage site
- \(AreaINF_f\): the area of in-field storage site
- \(CRFINS\): Capital recover factor storage site
- \(VCINF_f\): variable cost in-field storage site \(f\)
- \(PSF_{ts}\): period storage in in-field storage site

**Transportation**
- \(LC_{loader}\): loading cost loader
- \(ULC_{loader}\): unloading cost loader
- \(loadMass_{loader}\): loading mass loader
- \(L_{loader}\): loading time loader
- \(U_{loader}\): unloading time loader
- \(BP_t\): biomass produced at time period \(t\)
- \(FC_p\): fixed cost of transportation units
- \(N_{loader}\): number of loaders
- \(N_{semi-trucktrailer}\): number of semi-truck trailers
- \(N_{truck}\): number of truck
- \(VCT\): volume capacity transportation
- \(WCT\): weight capacity transportation
- \(N_{trips}\): the expected number of trips per month
- \(TBTSIR_{ijr,ts}\): tons of biomass transported from source site \(i\) to inventory \(j\) and then transferred to biorefinery site \(r\)
- \(TBTSFR_{ifr,ts}\): tons of biomass transported from source site \(i\) to in-field storage site \(f\) and then transferred to biorefinery site \(r\)
- \(N_{loading}\): number of loading
- \(VC_p\): variable cost of transportation units
- \(VCT_{semi-trucktrailer}\): variable cost transportation semi-truck trailer
- \(VCT_{truck}\): variable cost transportation truck
• $Speed_{semi-trucktrailer}$: speed semi-truck trailer
• $E_{semi-trucktrailer}$: efficiency semi-truck trailer
• $LoadMass_{semi-trucktrailer}$: loading mass semi-truck trailer
• $Speed_{truck}$: speed truck
• $E_{truck}$: efficiency truck
• $LoadMass_{truck}$: loading mass truck

Moisture content penalty
• $PenaltyCost$: penalty cost on extra amount of moisture content
• $MCI$: moisture content of biomass at inventory site
• $MCF$: moisture content of biomass at in-field storage site
• $MC$: moisture content of biomass before storing

Constraints
• $D_{ij}$: distance between farm $i$ and inventory site $j$ (km)
• $D_{fj}$: distance between in-field storage site $f$ and inventory site $j$ (km)
• $D_{jr}$: distance between inventory site $j$ to biorefinery site $r$ (km)
• $Length_t$: duration of time period $t$
• $LBI_j$: lower bound inventory $j$
• $UBI_j$: upper bound inventory $j$
• $Dens$: density of biomass
• $DEM_s$: demand of biomass in a time period $s$ (ton)
• $ACRELAND_i$: acre of land $i$ available for leasing
• $HeightI$: the height of inventory’s structure
• $BaleMass$: mass of each bale
• $BaleSize$: the size of each bale

Stochastic approach (weather scenarios)
• $\emptyset_w$: the weather factor for growing processes
• $\sigma_w$: the weather factor for harvesting/collecting processes
• $\varphi_w$: the production conversion factor
• $Pb_w$: the probability related to different weather scenarios

**Stochastic approach (moisture content scenarios)**
• $\gamma_k$: the moisture content factor for growing processes
• $\delta_k$: the moisture content factor for harvesting processes
• $\theta_k$: the moisture content factor for collecting processes
• $\omega_k$: the moisture content factor for Inventory processes
• $\theta_k$: the moisture content factor for In-field storage processes
• $\beta_k$: the moisture content factor for transportation processes
• $\alpha_k$: the moisture content factor for production processes
Defining sets

<table>
<thead>
<tr>
<th>Defined sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i = 1$: Source site</td>
</tr>
<tr>
<td>$j = 1$: Storage site</td>
</tr>
<tr>
<td>$f = 1$: In-field storage site</td>
</tr>
<tr>
<td>$r = 1$: Biorefinery site</td>
</tr>
<tr>
<td>$t = \text{JUN…OCT}$: Time</td>
</tr>
<tr>
<td>$s = \text{JUL…OCT}$: Time</td>
</tr>
<tr>
<td>$S_1$: combination of $t$ and $s$ permissible for Inventory</td>
</tr>
<tr>
<td>$S_2$: combination of $t$ and $s$ permissible for In-field storage</td>
</tr>
<tr>
<td>$w = 1...4$: Weather scenarios</td>
</tr>
<tr>
<td>$k = 1...4$: Moisture content scenarios</td>
</tr>
<tr>
<td>$e = 1...3$: Harvesting methods</td>
</tr>
<tr>
<td>$m = 1...3$: Collecting methods</td>
</tr>
<tr>
<td>$p = 1...2$: Transportation methods</td>
</tr>
</tbody>
</table>

6.4 Deterministic Approach

The first approach to modeling the problem is deterministic approach. In this part we are going to define a model in order to minimize the cost of biomass production, the amount of environmental impacts and energy consumption by the system without considering the uncertainties factors in the model.

6.4.1 Economic objective (Minimization of total annual cost)

**Production costs**

The cost of biomass cultivation can be assessed by equation 12. In this formula, by multiplying the amount of land under cultivation to the cost of biomass production, we can determine the value
of biomass production cost. The cost of biomass production includes various components such as
the cost of seeding, fertilizing, insecticide, crop insurance and so on. The amount of land under
cultivation could be determine by multiplying the leased acres of land times to the proportion of
land that we are going to cultivate. Equation 13 is used in order to calculate the acres of land under
cultivation process.

\[ BPC = \sum_{i=1}^{l} ALC_i \times CProduction \]  \hspace{1cm} (14)

\[ ALC = \sum_{i=1}^{l} Acrelease_i \times PP_i \]  \hspace{1cm} (15)

**Harvesting Cost**

The harvesting cost can be divided into two parts, the cost of harvesting machineries and the cost
of harvesting activities. The cost of harvesting machineries also can be divided into two parts,
fixed cost and variable cost. Fixed cost can be calculated by aggregation of fixed cost of
machineries times to the number of required machines. Furthermore, the variable cost is assessed
by multiplying the variable cost of harvesting machineries times to the number of available
harvesting hours. The cost of harvesting activities is a variable cost and it could be changed
according the tons of biomass harvested from the field. The amount of biomass harvested can be
assessed by the formula (18). The harvesting cost can be calculated by the following formula:

\[ HC = harvesting \text{ machineries costs} + harvesting \text{ activities cost} \]  \hspace{1cm} (16)

\[ HC = \left[ \sum_{e=1}^{E} (FC_e \times H_e) + \sum_{e=1}^{E} \sum_{t=1}^{T} (VCH_e \times H_e \times NAHWH_t) \right] + \]
\[ \left[ \sum_{i=1}^{l} \sum_{t=1}^{T} \sum_{e=1}^{E} (TBH_{it} \times HVcost_e \times H_e) \right] \]  \hspace{1cm} (17)

\[ TBH = \sum_{i=1}^{l} \sum_{t=1}^{T} ALC_i \times PP_l \times YADJ_t \times BYIELD_i \]  \hspace{1cm} (18)

**Harvesting units cost**

**Fixed cost harvesting units**

In order to assess the fixed costs of harvesting units, we can use the equations number 19, 20.
Fixed cost of machineries can be determined by the equation 19. In order to calculate the number of required machineries in baling unit, we can apply the equation number 21. 22.

\[
FC_e = \sum_{machine} (FC_{machine} \times N_{machine}), \forall (e)
\]  

\[
Fixed cost_{machineries} = \sum_{e=1}^{E} (FC_e \times H_e)
\]  

\[
Baling system
\]
Fixed cost of baling harvest unit can be determined by the equation 21. In order to calculate the number of required machineries in baling unit, we can apply the equation number 22, 23.

\[
FC_1 = [(FC_{windrower} \times N_{windrower}) + (FC_{Raker} \times N_{Raker}) + (FC_{Baler} \times N_{Baler}) + (FC_{Raker-tractor} \times N_{Raker-tractor}) + (FC_{Baler-tractor} \times N_{Baler-tractor})]
\]  

\[
N_{machine} = ROUND \left( \frac{EFC_{baler}}{EFC_{machine}} \right)
\]  

\[
N_{baler}^{*} = ROUND \left( \frac{EFC_{Unit} \times H_{Unit}}{EFC_{baler}} \right)
\]  

\[
Ensiling system
\]
Fixed cost related to the ensiling harvest unit can be calculated be the following formula:

\[
FC_2 = (FC_{combine} \times N_{combine})
\]  

\[
Chopping system
\]
Fixed cost regarding the chopping harvest unit can be determined by the equation 25.

\[
FC_3 = (FC_{forage\,harvester} \times N_{forage\,harvester})
\]  

\[
Variable cost\, harvesting\, units
\]
Variable cost harvesting units can be assessed by the following formula:

\[
VC_{machineries} = \sum_{e=1}^{E} \sum_{t=1}^{T} (VCH_e \times H_e \times NAHWH_t)
\]
The variable cost of machineries in each harvesting unit can be defined by the equation 27.

\[ V_{C_e} = \sum_{\text{machine}} (V_{C_{\text{machine}}} \times N_{\text{machine}}) \quad \forall (e) \]  

(27)

**Baling system**

The variable cost of baling harvest unit can be determined by the following formula:

\[ V_{CH_1} = [(V_{C_{\text{windrower}}} \times N_{\text{windrower}}) + (V_{C_{\text{Raker}}} \times N_{\text{Raker}}) + (V_{C_{\text{Baler}}} \times N_{\text{Baler}}) + (V_{C_{\text{Raker-tractor}}} \times N_{\text{Raker-tractor}}) + (V_{C_{\text{Baler-tractor}}} \times N_{\text{Baler-tractor}})] \]  

(28)

**Ensiling system**

The variable cost regarding the ensiling harvest unit can be calculated by the following formula:

\[ V_{CH_2} = V_{C_{\text{combine}}} \times N_{\text{combine}} \]  

(29)

**Chopping system**

The variable cost of chopping harvest unit can be calculated by the following formula:

\[ V_{CH_3} = V_{C_{\text{forageharvester}}} \times N_{\text{forage harvester}} \]  

(30)

**Collecting costs**

The collecting cost can be classified into two parts, the cost of collecting machineries plus to collecting activities cost. The fixed cost of collecting machineries can be calculated by aggregation of fixed cost of machineries times to the number of required machineries. Furthermore, the variable cost is assessed by multiplying the variable cost of collecting machineries times to the number of available collecting working hours. The cost of collecting activities is a variable cost and it could be changed according the tons of biomass collected from the field. In this study, the amount of biomass collected is assumed to be equal the amount of biomass harvested. The amount of biomass collected can be assessed by the equation number (32). The harvesting cost can be calculated by the following formula:
Collecting cost = machinery cost + collecting activities cost = $\sum_{m=1}^{M}(FC_m * C_m) + \sum_{m=1}^{M} \sum_{t=1}^{T}(VC_m * C_m * NACWH_t) + \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{m=1}^{M} TBCol_{it} * CLcost_m * C_m$

$TBCol_{it} = TBH_{it} , \forall(i,t)$

**Baling system**

In the baling collect unit the machinery cost relates to the cost of stinger stacker which could be assessed by the equations number (33-37):

machinery cost = Loading cost + Unloading cost + Operating cost

$Loading\ cost = \sum_{i=1}^{I} \sum_{t=1}^{T} \left[\frac{(1-\mu_{baler})^*BYIELD_i^*ALH_{it}}{BaleMass} * Cost_{stinger} * LT_{stinger}\right]$  

$Unloading\ cost = \sum_{i=1}^{I} \sum_{t=1}^{T} \left[\frac{(1-\mu_{baler})^*BYIELD_i^*ALH_{it}}{BaleMass} * Cost_{stinger} * ULT_{stinger}\right]$  

$Operating\ cost = \sum_{i=1}^{I} \sum_{t=1}^{T} \left[\frac{(2*D)}{S_{stinger}^*_i} * \frac{(1-\mu_{baler})^*BYIELD_i^*ALH_{it}}{LM_{stinger}^*_i} * Cost_{stinger}\right]$  

$ALH = \sum_{i=1}^{I} \sum_{t=1}^{T} ALC_{it} * PP_{it}$

**Ensiling system**

The ensiling collect unit cost can be assessed by the equations number (38-40):

machinery cost = Fixed cost + Variable cost

$FC_2 = (FC_{SilageWagon} * N_{SilageWagon}) + (FC_{SilageTractor} * N_{SilageTractor})$  

$VC_2 = [(VC_{SilageWagon} * N_{SilageWagon}) + (VC_{SilageTractor} * N_{SilageTractor})] * NACWH$
Chopping system
The cost related to chopping collect unit can be calculated by the equations number (41-43):

\[ \text{machinery cost} = \text{Fixed cost} + \text{Variable cost} \]  \hspace{1cm} (41)

\[ FC_3 = (FC_{\text{Forage Wagon}} \times N_{\text{Forage Wagon}}) + (FC_{\text{Forage Tractor}} \times N_{\text{Forage Tractor}}) \]  \hspace{1cm} (42)

\[ VC_3 = [(VC_{\text{Forage Wagon}} \times N_{\text{Forage Wagon}}) + (VC_{\text{Forage Tractor}} \times N_{\text{Forage Tractor}})] \times NACWH \]  \hspace{1cm} (43)

Inventory costs
In order to determine the total cost of inventory, it could be possible to classify this cost into two parts. The equations number (44-45) shows the total calculation of inventory costs.

\[ IC = \left[ \sum_{j=1}^{J} PriceSI_{j} \times Areal_{j} \times CRFStructure \right] + \]

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{\text{ts} \in S} (TBTSIR_{ijr,ts} \times VCS_{j} \times PSI_{ts}) + \]

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{\text{ts} \in S} (TBTSIR_{ijr,ts} \times \text{cost} \_ \text{drying} \times EVRate) \]  \hspace{1cm} (44)

\[ EVRate = Gflow \times (MC - 15\%) \]  \hspace{1cm} (45)

Cost Structure inventory
The fixed cost of inventory is relates to the cost of constructing the structure of the inventory, which can be assessed based on the amount of inventory area times to the construction cost and capital recovery factor of inventory’s structure. The following formulas (equations number 46-49) demonstrate the calculations regarding this cost.

\[ Cost \_ structure_{\text{inventory}} = \sum_{j=1}^{J} OCI_{j} = \sum_{j=1}^{J} PriceSI_{j} \times Areal_{j} \times CRFStructure \]  \hspace{1cm} (46)

\[ OCI_{j} = PStructure_{j} \times CRFStructure , \forall(j) \]  \hspace{1cm} (47)
\[ CRFStructure = \frac{i(1+i)^n}{(1+i)^n-1} \quad (n = 15, i = 8\%) \]  

\[ PStructure_j = PriceSI_j \cdot AreaI_j, \forall (j) \]  

**Variable cost storage**

The variable cost of inventory relates to the holding costs of feedstocks in the inventory plus the costs regarding the pretreatment method which is used in the process. The following equations (50-51) illustrate the calculation regarding this cost.

\[
\begin{align*}
\text{Variable costs}_{\text{inventory}} &= \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{ts} \left( TBSIR_{ijr,ts} \cdot VCS_j \cdot PSL_{ts} \right) + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{ts} \left( TBSIR_{ijr,ts} \cdot \text{cost}_{\text{drying}} \cdot EVRate \right) \right] \\
EVRate &= Gflow \cdot (MC - 15\%); \quad EVRate \geq 0 ;
\end{align*}
\]

**In-field storage cost (INFSC)**

The following formula (52) demonstrates the total calculation for assessing this cost. The procedure is similar to the inventory cost but here we didn’t consider the pre-treatment cost in this method.

\[
\begin{align*}
INFSC &= \text{Cost structure} + \text{Variable cost storage} = \left( \sum_{f=1}^{F} \left( PriceINF \cdot AreaINF_f \cdot CRFINFS \right) \right) + \left( \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{ts} \left( TBSFR_{ifr,ts} \cdot VCINF \cdot PSF_{ts} \right) \right) \\
\end{align*}
\]

**Cost structure**

The following formulas (equations number 53-56) demonstrate the calculations regarding this cost.

\[
\begin{align*}
\text{Cost structure}_{INF} &= \sum_{f=1}^{F} OCS_f = \sum_{f=1}^{F} PriceINF_f \cdot AreaINF_f \cdot CRFINFS \\
OCS_f &= PSINF_f \cdot CRFINFS, \forall (j)
\end{align*}
\]
\[ CRFSINF = \frac{i(1+i)^n}{(1+i)^n-1}; \quad (n = 7, i = 8\%) \quad (55) \]

\[ PSINF_f = PriceINF_f \times AreaINF_f, \forall(f) \quad (56) \]

**Variable cost storage**

The variable cost regarding in-field storage cost can be assessed by the following formula:

\[ VCINF = \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{t \in S_2} (TBSFR_{ifr,ts} \times VCINF_f \times PSF_{ts}) \quad (57) \]

**Transportation costs**

In order to calculate the total cost of transportation, it could be assessed by considering the cost of transportation unit plus to the cost of loading and unloading processes. The following equation (58) illustrates how it could be possible to calculate this cost.

\[ Transportation \ cost = TC_{transporters} + Loading \ and \ unloading \ cost \quad (58) \]

**Loading and unloading cost**

The cost of loading and unloading could be calculated by the following formulas (59-61):

\[ Loading \ and \ unloading \ cost = (LC_{loader} + ULC_{loader}) \times N_{loader} \quad (59) \]

\[ LC_{loader} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{p=1}^{P} \left[ \frac{BP_{it \_loadMass_{loader}}}{L_{loader} \times (FC_p \times TRN_p)} \right] \quad (60) \]

\[ ULC_{loader} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{p=1}^{P} \left[ \frac{BP_{it \_loadMass_{loader}}}{U_{loader} \times (FC_p \times TRN_p)} \right] \quad (61) \]

**Transportation unit cost**

The total cost related to the transportation unit can be assessed by the following equation:

\[ TC_{Transporters} = \sum_{p=1}^{P} [FC_p + VC_p] \times TRN_p \quad (62) \]
Fixed cost transportation unit

The fixed cost related to the transportation unit can be assessed by the following equations:

\[ FC_1 = (FC_{\text{semi-trucktrailer}} \times N_{\text{semi-trucktrailer}}) \] (63)

\[ FC_2 = (FC_{\text{truck}} \times N_{\text{truck}}) \] (64)

Variable cost transportation unit

The variable cost of transportation unit can be determined by the following formula (65):

\[
V_C_p = \left[ \left( \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{p=1}^{P} \sum_{t_s \in S_1} TBTSIR_{ijr,t_s} \times (D_{ij} + D_{jr}) \times VCT_p \right) + \right. \\
\left. \left( \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{p=1}^{P} \sum_{t_s \in S_2} TBTSFR_{ifr,t_s} \times (D_{if} + D_{fr}) \times VCT_p \right) \right]
\] (65)

The variable cost of each transporter can be assessed based on the equations number (66-67).

\[ VCT_1 = 2 \times \frac{FC_1}{\text{Speed}_{\text{semi-trucktrailer}} \times E_{\text{semi-trucktrailer}} \times \text{LoadMass}_{\text{semi-trucktrailer}}} \] (66)

\[ VCT_2 = 2 \times \frac{FC_2}{\text{Speed}_{\text{truck}} \times E_{\text{truck}} \times \text{LoadMass}_{\text{truck}}} \] (67)

The number of required transporters can be defined by the following formulas (68-69):

\[ N_{\text{semi-trucktrailer}} = \sum_{i=1}^{I} \sum_{t=1}^{T} \frac{BP_{it}}{WCT_1} \times TRN_1 \] (68)

\[ N_{\text{truck}} = \sum_{i=1}^{I} \sum_{t=1}^{T} \frac{BP_{it}}{WCT_2} \times TRN_2 \] (69)

The values regarding the weight capacity and volume capacity of each transporters can be assessed by the following equations (70-73):

\[ WCT_1 = W_{C_{\text{semi-trucktrailer}}} \times N_{\text{trips}} \] (70)
\[ WCT2 = WC_{truck} \times Ntrips \] (71)

\[ VlCT1 = VlC_{semi-trucktrailer} \times Ntrips \] (72)

\[ VlCT2 = VlC_{truck} \times Ntrips \] (73)

The expected number of trips for transportation unit can be assessed based on the following formula (74):

\[ Ntrips = \frac{\text{working hours}}{\text{cycle time}} \times \text{Length period} \] (74)

**Penalty cost on moisture content limit of feedstock**

In this work, we assumed a penalty cost regarding the extra moisture content of feedstocks. The following equation (75) illustrates the calculation of this cost.

\[ PCMC = \left( \sum_1^I \sum_1^J \sum_1^R \sum_{ts \in S_1} TBTSIR_{ijr,ts} \times (MCI - 15\%) + \sum_1^I \sum_1^F \sum_1^R \sum_{ts \in S_2} TBTSFR_{ifr,ts} \times (MCF - 15\%) \right) \times \text{PenaltyCost} \] (75)

**Supply constraints**

The amount of land under cultivation process can be determined by the following equation:

\[ ALC = \sum_{i=1}^I Acrelease_i \times PP_i \] (76)

It should be consider that the total amount of land that leased for cultivation is limited by the total acres the land.

\[ acre\ lease_i \leq ACRELAND_i, \forall (i) \] (77)

**Harvesting constraint**

The number of acres of land harvested can be calculated by the following equation:
\[ ALH = \sum_{i=1}^{I} \sum_{t=1}^{T} ALC_i * PP1_{it} \tag{78} \]

The total amount of biomass harvested can also be assessed by the following formula:

\[ TBH = \sum_{i=1}^{I} \sum_{t=1}^{T} ALH_{it} * YADJ_t * YIELD_t \tag{79} \]

We should consider this note that the number of available harvesting working hours is limited by the working length of a day.

\[ NAHWH_t \leq Length_t, \forall(t) \tag{80} \]

**Collecting constraint**

In this study, we assumed that the total amount of biomass harvested from the source site is equal to the total amount of biomass collected. Therefore, the amount of biomass produced from each farm at a time period \( t \) can be determined based on the following equations (81-84):

\[ TBCol_{ijfrts} = TBH_{lt} = PD_{lt}, \forall(i,j,f,r,ts) \tag{81} \]

\[ TBCol = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{t \in S_1} (TBSIR_{ijr,ts}) + \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{t \in S_2} (TBSFR_{ijr,ts}); NACWH_t \leq Length_t, \forall(t) \tag{82} \]

\[ PD_{contracted} = \sum_{i=1}^{I} \sum_{t=1}^{T} BP_{it} \tag{83} \]

\[ BP = \sum_{i=1}^{I} \sum_{t=1}^{T} Acrelease_i * PP_i * YADJ_t * Yield_i \tag{84} \]

**In-field storage constraint**

We should consider the capacity of in-field storage cost because the excesses biomass then should be stored on the ground and this could be increase the amount of moisture content and other related risks. Therefore, the amount of biomass that stored in the side of a field is limited by the capacity of the site that considered for this process. The following constraint illustrated this issue.
\[ \sum_{i=1}^{I} \sum_{r=1}^{R} TBTSFR_{ifr,ts} \leq CAPINF_f, \forall (f, ts \in S_2) \] (85)

Furthermore, the following constraint (86) shows that the amount of biomass that transferred from the source site to the biorefinery is equal to the amount of biomass that produced from a source site in a certain time period.

\[ \sum_{s:(0,s) \in S_2} TBTSFR_{ifr,0s} + \sum_{s:(0,s) \in S_1} TBTSIR_{ijr,0s} = BP_{i0}, \forall (i, f, j, r, t) \] (86)

**Storage constraint**

Following equations (87-88), illustrates that how the capacity of inventory site could be define.

\[ PcapI_j = AreaI_j * HeightI, \forall (j) \] (87)

\[ CAPI_j - (PcapI_j * \frac{BaleMass}{BaleSize}) = 0, \forall (j) \] (88)

The following constraint (89), demonstrates that the total amount of biomass transferred to the inventory site is limited by the capacity of it.

\[ \sum_{i=1}^{I} \sum_{r=1}^{R} TBTSIR_{ijr,ts} \leq CAPI_j, \forall (j, ts \in S_1) \] (89)

Based on the following constraint (90), the storage capacity should be being between its lower and upper bounds:

\[ LBI_j \leq UBI_j \leq CAPI_j, \forall (j) \] (90)

The following constraint (91) illustrates that the total inventory of all the feedstocks in terms of volume should not exceed the designed storage capacity:
\[ \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{r=1}^{R} \frac{TBSIR_{ijr,ts}}{(1-MC) \cdot Dens} \leq PCap_{j} \quad \forall (j, ts \in S_1) \] (91)

**Transportation constraint**

The following constraints (92-95) shows that the total amount of biomass that transferred to the biorefinery is limited by the amount of transportation unit capacities (weight and volume capacities).

\[ \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{r=1}^{R} \frac{TBSIR_{ijr,ts}}{(1-MC)} \leq VICT \quad \forall (ts \in S_1) \] (92)

\[ \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{r=1}^{R} \frac{TBSIR_{ijr,ts}}{(1-MC)} \leq WCT \quad \forall (ts \in S_1) \] (93)

\[ \sum_{i=1}^{l} \sum_{f=1}^{F} \sum_{r=1}^{R} \frac{TBSFR_{ifr,ts}}{(1-MCF)} \leq VICT \quad \forall (ts \in S_2) \] (94)

\[ \sum_{i=1}^{l} \sum_{f=1}^{F} \sum_{r=1}^{R} \frac{TBSFR_{ifr,ts}}{(1-MCF)} \leq WCT \quad \forall (ts \in S_2) \] (95)

The following equations (96-97) define the amount of weight and volume capacity of transportation unit.

\[ WCT = WCT1 \cdot N_{semi-truck} + WCT2 \cdot N_{truck} \] (96)

\[ VICT = VICT1 \cdot N_{semi-truck} + VICT2 \cdot N_{truck} \] (97)

**Demand constraint**

The following constraint (98) illustrates that the total amount of biomass that transferred to the biorefinery at each time period should be equal to the demand of biorefinery.

\[ \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{r=1}^{R} \sum_{t:(t,s) \in S_1} TBSIR_{ijr,ts} + \sum_{i=1}^{l} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{t:(t,s) \in S_2} TBSFR_{ifr,ts} = DEM_{s} \quad \forall (s) \] (98)
**Binary variable constraint**

The following equations define the selection of proper methods for biomass production steps.

\[ \sum_{e=1}^{E} H_e - 1 = 0 \; ; \sum_{m=1}^{M} C_m - 1 = 0 \; ; \sum_{p=1}^{P} TRN_p - 1 = 0 \]  \hspace{1cm} (99)

\[ H_1 = C_1 \; ; H_2 = C_2 \; ; H_3 = C_3 \; ; TRN_1 = H_1 \; ; TRN_2 = H_2 + H_3 \]  \hspace{1cm} (100)

**Logical constraint**

All the variables should be non-negative.

6.4.2 Second Objective function

**Minimizing the environmental impact**

To assess the environmental impacts, it is urgent to adopt a global approach, which can be able to determine the impacts of the system under investigation over the entire life cycle. In this study, LCA methodology considered to investigate and assess the environmental impacts of the system (Zamboni, Bezzo and Shah, 2009). According to this method, a set of LCA stages Z, which is required for further calculations, are defined in equation (101).

[Biomass cultivation (BCU), biomass harvesting (BH), biomass collecting (BCO), biomass storage (BS), biomass transportation (BT)]

\[ z \in Z = \{BCU,BH,BCO,BS,BT\} \]  \hspace{1cm} (101)

**Environmental objective function**

\[ Objective \ function = \text{Min} (T I O T) = \text{Min}(\sum_{t} T I_{t}) \]  \hspace{1cm} (102)

\( T \text{IOT} \) estimated by summing the biomass supply chain annual impact over time \( (T I_{t}) \) either on global warming \( \left[ \frac{kg \; CO_2}{\text{eq} \; \text{year}} \right] \) or on water resource depletion \( \left[ \frac{m^3 \; H_2O}{\text{year}} \right] \) (Zamboni, Bezzo and Shah, 2009).
The impact factor ($TI_t$) which demonstrated in the equation (103) needs to consider the impact of the biomass supply chain’s operations on environment per each LCA stages $Z$ (equation 104).

$$TI_t = \sum_z Imp_{zt} \quad \forall t$$  \hspace{1cm} (103)

$$Imp_{zt} \left[ \frac{kg \text{ CO}_2 - eq}{year} \text{ or } \frac{m^3 H_2O}{year} \right]$$  \hspace{1cm} (104)

The impact rate $Imp_{zt}$ is determined by applying an impact factor $f_z \left[ \frac{kg \text{ CO}_2 - eq}{year} \text{ or } \frac{m^3 H_2O}{year} \right]$ for the biomass at stage $(z)$ to a reference flow $f_z \left[ \text{Unit} \frac{year}{year} \right]$, which is specific to LCA stage $z$ (table 26) at time $t$ (Zamboni, Bezzo and Shah, 2009). The following equation (105) demonstrated this issue.

$$Imp_{zt} = f_z * f_{zt} \quad \forall t, Z \in \{CF, WF\}$$  \hspace{1cm} (105)

Table 26: LCA stages $Z$

<table>
<thead>
<tr>
<th>BCU (biomass cultivation)</th>
<th>Cultivation practices, geographical region of source site</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH (biomass harvesting)</td>
<td>Harvesting work hours, methods and unit types</td>
</tr>
<tr>
<td>Impact Factor</td>
<td>BCO (biomass collecting)</td>
</tr>
<tr>
<td></td>
<td>Collecting work hours, methods and unit types</td>
</tr>
<tr>
<td>BS (biomass storage)</td>
<td>Biomass type, storage methods</td>
</tr>
<tr>
<td>BT (biomass transportation)</td>
<td>Distance traveled, transportation modes</td>
</tr>
</tbody>
</table>

The amount of objective function can be defined by the following formula:

$$Objective \ function = Min (TIOT) = Min(\sum_t TI_t)$$  \hspace{1cm} (106)

**Biomass Cultivation (BCU)**

The amount of impact factor for biomass cultivation process can be assessed based on the following formulas (107-108):
\[ \text{Imp}_{i,\text{BCU}} = \sum_{l=1}^{l} (f_{i,\text{BCU}} \times ALC_i) \]  
\[ ALC = \sum_{i=1}^{l} \text{Acrelease}_i \times PP_i \]

Where;
- \[ f_{i,\text{BCU}} \left( \frac{kg \ CO_2}{acre} \right) \text{ or } \left( \frac{m^3 H_2O}{acre} \right) \] : Impact factor biomass cultivation in field \( i \)
- \( ALC_i [acre] \) : Acres of field \( i \) which cultivated

**Biomass harvesting (BH)**

The impact factor regarding the biomass harvesting process can be determined according to the following formula (109-110):

\[ \text{Imp}_{i,t,\text{BH}} = \sum_{l=1}^{l} \sum_{t=1}^{T} (f_{i,\text{BH}} \times TBH_{i,t}) \]  
\[ TBH = \sum_{i=1}^{l} \sum_{t=1}^{T} ALC_i \times PP1_{it} \times YADJ_t \times YIELD_i \]

Where;
- \[ f_{i,\text{BH}} \left( \frac{kg \ CO_2}{ton} \right) \text{ or } \left( \frac{m^3 H_2O}{ton} \right) \] : impact factor harvesting biomass from source site \( i \)
- \( TBH_{i,t} [ton] \) : tons of biomass harvested from source site \( i \) at time period \( t \)

**Biomass collecting (BCO)**

The amount of impact factor relate to the biomass collection process can be defined based on the following formulas (111-112):

\[ \text{Imp}_{i,t,\text{BCO}} = \sum_{l=1}^{l} \sum_{t=1}^{T} (f_{i,\text{BCO}} \times TBCol_{i,t}) \]  
\[ TBCol = TBH = \sum_{i=1}^{l} \sum_{t=1}^{T} ALC_i \times PP1_{it} \times YADJ_t \times YIELD_i \]
Where;

- \( f_{BCO} \left[ \frac{kg \, CO_2-equ}{ton} \right. \) or \( \frac{m^3 \, H_2O}{ton} \) : impact factor collecting biomass from source site \( i \)
- \( TBCol_i[ton] \) : tons of biomass collected from source site \( i \) at time period \( t \)

**Biomass storage (BS)**

The amount of impact factor related to the different types of storage can be assessed according to the following formulas (113-114):

\[
Imp_{BS,t} = \sum_{i=1}^{l_i} \sum_{j=1}^{l_j} \sum_{r=1}^{R} \sum_{t_s \in S_1}(f_{j\,BSi} \times TBTSIR_{ijr,ts} \times PSI_{ts}) + \sum_{i=1}^{l_i} \sum_{f=1}^{l_f} \sum_{t_s \in S_2}(f_{f\,BSf} \times TBTSFR_{ifr,ts} \times PSF_{ts})
\] (113)

\[
Imp_{BS,t} = \sum_{i=1}^{l_i} \sum_{j=1}^{l_j} \sum_{r=1}^{R} \sum_{t_s \in S_1}(f_{j\,BSi} \times TBTSIR_{ijr,ts} \times PSI_{ts}) + \sum_{i=1}^{l_i} \sum_{f=1}^{l_f} \sum_{t_s \in S_2}(f_{f\,BSf} \times TBTSFR_{ifr,ts} \times PSF_{ts})
\] (114)

Where;

- \( f_{j\,BSi} \left[ \frac{kg \, CO_2-equ}{ton} \right. \) or \( \frac{m^3 \, H_2O}{ton} \) : Impact factor storage biomass at Inventory site \( j \)
- \( f_{f\,BSf} \left[ \frac{kg \, CO_2-equ}{ton} \right. \) or \( \frac{m^3 \, H_2O}{ton} \) : Impact factor storage biomass at in-field storage site \( f \)
- \( TBTSIR_{ijr,ts}[ton] \) : tons of biomass stored in inventory site \( j \) and transferred to biorefinery at time period \( ts \)
- \( TBTSFR_{ifr,ts}[ton] \) : tons of biomass stored at in-field site \( f \) and transferred to biorefinery at time period \( ts \)

**Biomass transportation (BT)**

The amount of impact factor regarding the transportation unit can be defined based on the following equation (115):

\[
Imp_{BT,t} = (\sum_{i=1}^{l_i} \sum_{j=1}^{l_j} \sum_{r=1}^{R} \sum_{t_s \in S_1}(f_{i\,BTi} \times TBTSIR_{ijr,ts} \times (D_{ij} + D_{jr} \times \tau_{ir}))) + (\sum_{i=1}^{l_i} \sum_{f=1}^{l_f} \sum_{t_s \in S_2}(f_{i\,BTf} \times TBTSFR_{ifr,ts} \times (D_{if} + D_{fr} \times \tau_{ir})))
\] (115)
Where;

- $f_{BTR}$: impact factors that measured as $\left[ \frac{kg \, CO_2-eq}{ton \, km} \right.$ or $\left. \frac{m^3 \, H_2O}{ton \, km} \right]$ (for both truck and semi-trailer truck)

- Reference flow = delivery distance * amount of biomass transferred

- Delivery distance = $D_{xy}$ (direct route between centers) * $\tau_{xy}$ (tortuosity factor)

- $\tau_{xy}$ (tortuosity factor): (1.3) for suburban ($D_{jr}, D_{ij}, D_{fr}$)

6.4.3 Third objective function (Efficiency)

In the third objective function, to obtain maximum efficiency in the system we need to minimize the amount of energy we use in different processes of biomass production and delivery to biorefinery (Kumar and Sokhansanj, 2007). Therefore, in this regard, we are going to minimize the amount of energy consumption in each process of biomass production, harvesting, collecting, storage and transportation.

**Biomass production (cultivation)**

The energy consumption per unit of biomass cultivation process is defined by $ECP \left( \frac{MJ}{acre} \right)$. Therefore, the amount of energy used for biomass cultivation can be assessed by the following formulas (116-117):

$$
Energy \, consumption_{cultivation} = \sum_{i=1}^{l} ALC_i \times ECP
$$

$$
ALC = \sum_{i=1}^{l} Acrelease_i \times PP_i
$$

**Biomass harvesting**

To calculate the amount of energy utilization for biomass harvesting process, we need to define $ECH \left( \frac{MJ}{ton} \right)$ as the energy consumption per unit of biomass harvesting process. Therefore, the amount of consumed energy in harvesting process can be gained from the following equations (118-119):
Energy consumption\textsubscript{harvesting} = \sum_{i=1}^{I} \sum_{t=1}^{T} TBH_{it} \ast ECH \tag{118}

TBH = \sum_{i=1}^{I} \sum_{t=1}^{T} ALC_{i} \ast PP1_{it} \ast YADJ_{t} \ast YIELD_{i} \tag{119}

Biomass collecting

The energy consumption per unit of biomass collecting process is termed \( ECC(MJ\ ton) \) and the amount of energy usage can be determined by the following formulas (120-121):

Energy consumption\textsubscript{collecting} = \sum_{i=1}^{I} \sum_{t=1}^{T} TBCol_{it} \ast ECC \tag{120}

TBCol = TBH = \sum_{i=1}^{I} \sum_{t=1}^{T} ALC_{i} \ast PP1_{it} \ast YADJ_{t} \ast YIELD_{i} \tag{121}

Biomass storage

The energy consumption per unit of biomass storing process is termed \( ECS(MJ\ ton\ month) \) and the amount of energy usage for both inventory and in-field storage can be calculated by the following equation (122):

Energy consumption\textsubscript{collecting} = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{ts \in S_{1}} TBTSIR_{ijr,ts} \ast PSI_{ts} \ast ECSI + \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{ts \in S_{2}} TBTSFR_{ifr,ts} \ast PSF_{ts} \ast ECSINF \tag{122}

Biomass transportation

The energy consumption per unit of biomass transportation process is termed \( ECT(MJ\ ton\ -km) \) and the amount of energy usage can be assessed by the following formula (123):

Energy consumption\textsubscript{transportation} = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{ts \in S_{1,2}} (TBTSIR_{ijr,ts} + TBTSFR_{ifr,ts}) \ast DisIR \ast ECT \tag{123}
6.5 Model development under alternative Scenarios

6.5.1 Weather Scenarios

In the real world, the maximum production capacity of a farm is related to a combination of several factors such as frequency and the availability of harvesting equipment. These factors are deterministic in the sense that they can be determined prior to the actual period of production horizon. However, there are other uncertain features which influence the amount of production and they are mainly associated with weather conditions (Sharma, 2012).

The model defined in the previous chapter was the deterministic one, which we have the prior knowledge of the cutting frequency and the availability of the equipment. In addition, the dominant weather conditions were presumed to be in good condition and a pre-determined maximum production capacity was defined. However, changes in weather conditions could alter the amount of production. Therefore, in this part, the original model is changed accordingly to deal with these changes. The weather factor is classified into two mechanisms:

- First, growing season weather, which can be described as the weather condition throughout the real situation of crop growing.
- Second, harvest/collect weather, which is described as the weather situations throughout the harvesting/collecting months.

In this study, the actual weather condition is defined as a combination of growing season weather and harvesting/collecting weather. In this regard, if we consider the June as a harvesting month, then the prevalent weather conditions over the previous six months could define the growing season weather. Harvesting weather conditions are determined by the weather situations throughout the harvesting month (Cundiff, Dias and Sherali, 1997). The weather conditions can be classified as follows:

1. Growing weather conditions
   - Favorable
   - Unfavorable
2. Harvesting/collecting weather conditions

- Favorable
- Unfavorable

The actual weather condition is represented as some combination of the growing and harvesting weather condition (Cundiff, Dias and Sherali, 1997). Given the above classification, the weather-related scenarios can be represented by one of four states (W=1…, 4). A production conversion factor was also defined to consider both growing and harvesting/collecting factors in biomass production.

Table 27: Weather related factors for growing and harvesting processes

<table>
<thead>
<tr>
<th>Overall weather scenarios W</th>
<th>Growing season</th>
<th>Harvesting/collecting season</th>
<th>Production conversion factor</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>condition</td>
<td>Factor $\varnothing$</td>
<td>condition</td>
<td>Factor $\sigma$</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>1.0</td>
<td>F</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>1.0</td>
<td>INF</td>
<td>0.85</td>
</tr>
<tr>
<td>3</td>
<td>INF</td>
<td>0.95</td>
<td>F</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>INF</td>
<td>0.95</td>
<td>INF</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The revised model was formulated to deal with uncertainties due to the weather conditions. Accordingly, the following notations are defined:

- $\varnothing_w$: Weather condition factor, which affect the growing process of biomass during the growing season, based on the weather scenario $W$.

- $\sigma_w$: Weather condition factor, which affect the biomass harvesting /collecting process based on the weather scenario $W$. 

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• $\varphi_w$: Production conversion factor, which affect the production levels of biomass, based on the weather scenario $W$.

• $P_{bw}$: Probability associated with the weather condition being in state $W$. (we should consider this point that $\sum_{w=1}^{W} P_{bw} = 1$)

• $ALC_{iw}$: Acre of land $i$ cultivated under the weather scenario $W$.

• $TBH_{itw}$: Tons of biomass harvested from field $i$ at time period $t$ under the weather scenario $W$.

• $NAHWH_{tw}$: Number of available harvesting working hours at time period $t$ under weather scenario $W$.

• $TBCol_{itw}$: Tons of biomass collected from field $i$ at time period $t$ under weather scenario $W$.

• $ALH_{itw}$: Acre of land harvested from field $i$ at time period $t$ under weather scenario $W$.

• $NACWH_{tw}$: Number of available collecting working hours at time period $t$ under weather scenario $W$.

• $TBTSFR_{ifr,tsw}$: Tons of biomass transfer from source site $i$ to in-field storage site $f$ and then to biorefinery $r$, at time period $ts \in S_2$ under weather scenario $W$.

• $BP_{lw}$: Amount of biomass produced from field $i$ at time period $t$ under weather scenario $W$.

(We should also consider that the variables related to the covered storage would not affected by the weather scenarios so that is why we do not use index $W$ for defining them.)

**Stochastic Approach (weather scenarios)**

**Economic objective (Minimization of total annual cost)**
Production costs
The production cost under each weather scenarios can be assessed by the following equations (124-125):

\[ PC = \sum_{i=1}^{I} \sum_{w=1}^{W} ALC_{iw} \times C_{production} \]  
(124)

\[ ALC = \sum_{i=1}^{I} \sum_{w=1}^{W} Acrelease_{i} \times PP_{i} \times \phi_{w} \times P_{b_{w}} \]  
(125)

Harvesting Cost
The total harvesting cost under each weather scenarios can be calculated by the following formulas (126-128).

\[ HC = [\sum_{e=1}^{E} (FC_{e} \times H_{e}) + \sum_{t=1}^{T} \sum_{w=1}^{W} (VCH_{e} \times H_{e} \times NAHW_{t} \times \sigma_{w} \times P_{b_{w}})] + \]  
\[ [\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{e=1}^{E} \sum_{w=1}^{W} (TBH_{itw} \times HVCost_{e} \times H_{e})] \]  
(126)

\[ TBH = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} ALC_{iw} \times PP1_{it} \times YADJ_{t} \times BYIELD_{i} \times \sigma_{w} \times P_{b_{w}} \]  
(127)

\[ NAHW_{t} = NAHW_{t} \times \sigma_{w} \times P_{b_{w}} \]  
(128)

Collecting costs
The collecting cost regarding each weather scenarios can be assessed by determining the cost of each collection units.

\[ CC = [\sum_{m=1}^{M} (FC_{m} \times C_{m}) + \sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{w=1}^{W} (VC_{m} \times C_{m} \times NAHW_{t} \times \sigma_{w} \times P_{b_{w}})] + \]  
\[ [\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{w=1}^{W} (TC_{olitw} \times CLCost_{m} \times C_{m})] \]  
(129)

Baling system
The cost of baling collection unit can be calculated by the following formulas for each weather scenario w (130-134):
machinery cost = Loading cost + Unloading cost + Operating cost

\[ \text{Loading cost} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} \left[ \frac{(1-\mu_{\text{baler}}) \cdot \text{YIELD}_{i} \cdot \text{ALH}_{lw}}{\text{BaleMass}} \right] \cdot \text{Cost}_{\text{stinger}} \cdot \text{LT}_{\text{stinger}} \] (131)

\[ \text{Unloading cost} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} \left[ \frac{(1-\mu_{\text{baler}}) \cdot \text{YIELD}_{i} \cdot \text{ALH}_{lw}}{\text{BaleMass}} \right] \cdot \text{Cost}_{\text{stinger}} \cdot \text{ULT}_{\text{stinger}} \] (132)

\[ \text{Operating cost} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} \left[ \frac{(2 \cdot D) \cdot \text{S}_{\text{stinger}} + (1-\mu_{\text{baler}}) \cdot \text{YIELD}_{i} \cdot \text{ALH}_{lw}}{\text{LM}_{\text{stinger}}} \right] \cdot \text{Cost}_{\text{stinger}} \] (133)

\[ \text{ALH} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} \text{ALC}_{lw} \cdot \text{PP1}_{lt} \] (134)

**Ensiling system**

The cost of ensiling collection unit can also be calculated by the following formulas under each weather scenario \( w \) (135-138):

\[ \text{machinery cost} = \text{Fixed cost} + \text{Variable cost} \] (135)

\[ \text{FC}_2 = (\text{FC}_{\text{SilageWagon}} \cdot N_{\text{SilageWagon}}) + (\text{FC}_{\text{SilageTractor}} \cdot N_{\text{SilageTractor}}) \] (136)

\[ \text{VC}_2 = [(\text{VC}_{\text{SilageWagon}} \cdot N_{\text{SilageWagon}}) + (\text{VC}_{\text{SilageTractor}} \cdot N_{\text{SilageTractor}})] \cdot \text{NACWH}_{t} \cdot \sigma_{w} \cdot P_{b_{w}} \] (137)

\[ \text{NACWH} = \text{NACWH}_{t} \cdot \sigma_{w} \cdot P_{b_{w}} \] (138)

**Chopping system**

The cost related to the chopping collection unit can be assessed based on the following equations for each weather scenario \( w \) (139-142):

\[ \text{machinery cost} = \text{Fixed cost} + \text{Variable cost} \] (139)
\[ FC_3 = (FC_{ForageWagon} \times N_{ForageWagon}) + (FC_{ForageTractor} \times N_{ForageTractor}) \]  

(140)

\[ VC_3 = [(VC_{ForageWagon} \times N_{ForageWagon}) + (VC_{ForageTractor} \times N_{ForageTractor})] \times \]

\[ NACWH_t \times \sigma_w \times P_b_w \]  

(141)

\[ NACWH = NACWH_t \times \sigma_w \times P_b_w \]  

(142)

**Inventory costs**

The Inventory cost does not affect by weather scenarios because this type of storage is covered by a structure and protected from weather effects. The following equation (143) shows the calculation of inventory cost.

\[ IC = [\sum_{j=1}^{l} \text{PriceSI}_j \times \text{Area}_j \times CRFStructure] + \]

\[ \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{r=1}^{R} \sum_{t \in S_1} \left( TBTSIR_{ijr,ts} \times VCS_j \times PSI_{ts} \right) + \]

\[ \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{r=1}^{R} \sum_{t \in S_2} \left( TBTSIR_{ijr,ts} \times \text{cost}_\text{drying} \times EVRate \right) ] \]  

(143)

**In-field storage cost (INFSC)**

This type of storage is affected by weather factors because the biomasses is unprotected in this type of storage. Therefore, the following equation (144) demonstrated the cost related to this type of storage based on each weather scenarios.

\[ INFSC = \text{Fixed cost} + \text{Variable cost} = \left( \sum_{f=1}^{F} \left( \text{PriceINF} \times \text{AreaINF}_f \times CRFINF \right) \right) + \left( \sum_{i=1}^{l} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{w=1}^{W} \sum_{t \in S_2} \left( TBTSFR_{ifr,tsw} \times P_b_w \times VCINF_f \times PSF_{ts} \right) \right) \]  

(144)

**Transportation costs**

The cost of transportation unit under each weather scenarios can be calculated by the following formulas (145-147):
Transportation cost \[ = \left[ \sum_{p=1}^{P} [FC_p + VC_p] \times TRN_p \right] + \\
\left( \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{s=1}^{S_1} BP_{load}^{i,j,r,s} \times L_{loader} \times \left( FC_p \times TRN_p \right) \right) + \\
\sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{w=1}^{W} BP_{tw}^{i,f,r,w} \times U_{loader} \times \left( FC_p \times TRN_p \right) \right] \times N_{loader} \tag{145}
\]

\[ VC_p = \left( \left( \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{s=1}^{S_1} TBTSIR_{i,r,s} \times (D_{ij} + D_{jr}) \times VCT_p \right) + \\
\left( \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{w=1}^{W} \sum_{s=2}^{S_2} TBTSFR_{i,f,r,s} \times PBw \times (D_{if} + D_{fr}) \times VCT_p \right) \right) \]
\[ TC_{Transportation} = \sum_{p=1}^{P} [FC_p + VC_p] \times TRN_p \tag{146} \]

Penalty cost on moisture content limit of feedstock

The amount of penalty cost under each weather scenario can be determined by the following equation (148):

\[ PCM = \left( \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{s=1}^{S_1} TBTSIR_{i,r,s} \times (MC) - 15\% \right) + \\
\sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{w=1}^{W} \sum_{s=2}^{S_2} TBTSFR_{i,f,r,s} \times PBw \times (MCF - 15\%) \right) \times PenaltyCost \tag{148} \]

Supply constraints

The amount of land under cultivation in each weather scenarios can be defined by the following equation (149):

\[ ALC = \sum_{i=1}^{I} \sum_{w=1}^{W} Acrelease_i \times PP_i \times \phi_w \times PBw \]
\[ acrelease_i \leq ACRELAND_i , \forall (i) \tag{149} \]

Harvesting constraint

The amount of land harvested under each weather scenarios can be assessed by the following formulas (151-153):
\[ ALH = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} ALC_{tw} \cdot PP_{1t} \]  
(151)

\[ TBH = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} ALC_{tw} \cdot PP_{1t} \cdot YADJ_{t} \cdot BYIELD_{t} \cdot \sigma_{w} \cdot P_{bw} \]  
(152)

\[ NAHWH_{t} \leq Length_{t} \quad , \forall (t) \]  
(153)

Collecting constraint

The amount of biomass collected under each weather scenarios can be defined based on the following formulas (154-156):

\[ TBCol_{ijfrwts} = TBH_{itw} = PD_{tw} \quad , \forall (i,j,f,r,w,ts) \]  
(154)

\[ TBCol = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{ts \in S_{1}} (TBTSIR_{ijr,ts}) + \]  
\[ \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{w=1}^{W} \sum_{ts \in S_{2}} (TBTSFR_{ifrwt,ts} \cdot P_{bw}) \]  
(155)

\[ NACWH_{t} \leq Length_{t} \quad , \forall (t) \]  
(156)

The amount of biomass production under each weather scenarios can be calculated based on the following equations (157-158):

\[ PD_{contracted} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} BP_{itw} \]  
(157)

\[ BP = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{w=1}^{W} Acrease_{i} \cdot PP_{i} \cdot YADJ_{t} \cdot Yield_{i} \cdot \phi_{w} \cdot P_{bw} \]  
(158)

In-field storage constraint

According to the following formula (159), the amount of biomass transferred to the in-field storage site under each weather scenarios is limited by the capacity of this site.

\[ \sum_{i=1}^{I} \sum_{r=1}^{R} TBTSFR_{ifr,tsw} \leq CAPINF_{f} \quad , \forall (f,ts \in S_{2},w) \]  
(159)
Moreover, based on the following equation (160), the amount of biomass transferred from source site to the inventory or in-field storage site under each weather scenarios should be equal to the amount of biomass produced at each time period and weather scenarios.

\[
\sum_{s:(0,s) \in S_2} T_BTSSF_{i;r,0;sw} \cdot P_b_w + \sum_{s:(0,s) \in S_1} T_BTTSIR_{i;r,0;sw} = B_P_{i;0;w} \cdot \varphi_w \cdot P_b_w, \forall (i, j, r, t, w)
\]  

(160)

Storage constraint

\[
\sum_{j=1}^{J} \sum_{r=1}^{R} T_BTTSIR_{i;j;r,ts} \leq CAPI_j, \forall (j, ts \in S_1)
\]

(161)

Storage capacity should be being between its lower and upper bounds:

\[
LBI_j \leq UBI_j \leq CAPI_j, \forall (j)
\]

(162)

The total inventory of all the feedstocks in terms of volume should not exceed the designed storage capacity:

\[
\sum_{j=1}^{J} \sum_{r=1}^{R} \frac{T_BTTSIR_{i;j;r,ts}}{(1-\Delta) \cdot Dens} \leq PCapI_j, \forall (j, ts \in S_1)
\]

(163)

Transportation constraint

The amount of biomass transferred by transportation units under each weather scenarios is limited by the weight and volume capacity of transportation unit. The following constraints (164-169) illustrated this issue.

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \frac{T_BTTSIR_{i;j;r,ts}}{(1-\Delta) \cdot Dens} \leq V\text{ICT}, \forall (ts \in S_1)
\]

(164)

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \frac{T_BTTSIR_{i;j;r,ts}}{(1-\Delta) \cdot Dens} \leq W\text{CT}, \forall (ts \in S_1)
\]

(165)
\[ \sum_{l=1}^{\ell} \sum_{f=1}^{F} \sum_{r=1}^{R} \frac{TBTSR_{ifr,tsw}^*P_{bw}}{(1-MCF)\cdot \text{Dens}} \leq VlCT, \forall (ts \in S_2, w) \]  

(166)

\[ \sum_{l=1}^{\ell} \sum_{f=1}^{F} \sum_{r=1}^{R} \frac{TBTSR_{ifr,tsw}^*P_{bw}}{(1-MCF)} \leq WCT, \forall (ts \in S_2, w) \]  

(167)

\[ WCT = WCT1 \times N_{\text{semi-trucktrailler}} + WCT2 \times N_{\text{truck}} \]  

(168)

\[ VlCT = VlCT1 \times N_{\text{semi-trucktrailler}} + VlCT2 \times N_{\text{truck}} \]  

(169)

**Demand constraint**

The following equation (170) shows that the amount of biomass transferred to the biorefinery at each time periods under each weather scenarios should be equal to the demand of biorefinery.

\[ \sum_{l=1}^{\ell} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{:\{t,s\} \in S_1} TBTSIR_{ijr,ts} + \sum_{l=1}^{\ell} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{:\{t,s\} \in S_2} TBTSR_{ifr,tsw}^*P_{bw} = DEM_s, \forall (s, w) \]  

(170)

**Binary variable constraint**

\[ \sum_{e=1}^{E} H_e - 1 = 0 ; \sum_{m=1}^{M} C_m - 1 = 0 ; \sum_{p=1}^{P} TRN_p - 1 = 0 \]  

(171)

\[ H_1 = C_1 ; H_2 = C_2 ; H_3 = C_3 ; TRN_1 = H_1 ; TRN_2 = H_2 + H_3 \]  

(172)

**Logical constraint**

All the variables should be non-negative.

6.5.2 Moisture content scenarios

The amount of water content in the feedstocks is defined as percentage of moisture content. Reduction of dampness in feedstocks requires a pretreatment method such as drying which costs based on the crop’s wetness percentage.
In the baling system, moistness can significantly affect the production of large square bales. The ideal percentage of feedstocks humidity in baling system is a range between 18 – 22 % for dry harvest based on the crop type. Low moisture content at the time of harvest causes dry matter losses from crushing and fire danger from both high respiration rates within the cells of the biomass and mold growth. Moisture content can also significantly affect the density of bales. In regions with dry condition, wet storage is the proper option for storing switchgrass (Digman et al., 2010). Applying this method brings some advantages such as reduction of harvesting costs, lower DML during storage, improved switchgrass cell wall recovery during enzymatic hydrolysis and lower potential risk of fire during storage (Digman et al., 2010). However, there are some disadvantages related to this type of storage such as high equipment and storage structure costs (Collins and Owens, 2003). The wet storage method was found to be more expensive than other collection and storage methods for cellulosic refinery sizes greater than 1,500 Mg switchgrass per day due to the excessive cost of the ensiling pit and transference of damp feedstocks by truck (Kumar and Sokhansanj, 2007). The moisture content of biomass can affect each processes of biomass production from harvesting, collecting, storage and transportation.

Table 28: Moisture content related factors in biomass logistics

<table>
<thead>
<tr>
<th>MC (%)</th>
<th>Harvesting factor</th>
<th>Collecting factor</th>
<th>Inventory factor</th>
<th>In-field storage factor</th>
<th>Transportation factor</th>
<th>Production conversion factor</th>
<th>PbMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.85</td>
<td>1</td>
<td>1.2</td>
<td>1.4</td>
<td>1</td>
<td>1.428</td>
<td>0.2</td>
</tr>
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<td>0.98</td>
<td>1.1</td>
<td>1.3</td>
<td>0.95</td>
<td>1.198197</td>
<td>0.3</td>
</tr>
<tr>
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<td>1</td>
<td>0.95</td>
<td>1</td>
<td>1</td>
<td>0.9</td>
<td>0.855</td>
<td>0.3</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
<td>0.85</td>
<td>0.765</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The revised model was formulated to deal with uncertainties due to the moisture content of biomass. Accordingly, the following notations are defined:

- \( PbMC_k \): Probability related to each moisture content scenario \( k \).

- \( TBH_{itk} \): Tons of biomass harvested from field \( i \) at time period \( t \) with moisture content scenario \( k \).
• **BYIELD</noBreak>_{ik}**: Biomass yield of field \(i\) with moisture content \(k\).

• \(\delta_k\): harvesting factor related to moisture content scenario \(k\).

• \(ALH_{itk}\): Acre of land harvested from field \(i\) at time period \(t\) with moisture content scenario \(k\).

• \(\vartheta_k\): collecting factor related to each moisture content scenarios.

• \(\omega_k\): Inventory factor related to each moisture content scenarios.

• \(TBTSIR_{ijrk,ts}\): Tons of biomass transported from source site \(i\) to inventory \(j\) and then to biorefinery \(r\), at time period \(ts \in S_1\) and moisture content scenario \(k\).

• \(\theta_k\): In-field storage factor related to the moisture content scenario \(k\).

• \(TBTSFR_{ifrktsw}\): Tons of biomass transferred from source site \(i\) to in-field storage site \(f\) and then to biorefinery \(r\), at time period \(ts \in S_2\) and moisture content scenario \(k\).

• \(\beta_k\): Transportation factor related to the moisture content scenario \(k\).

• \(BP_{itk}\): Biomass production from field \(i\) at time period \(t\) with moisture content scenario \(k\).

**Stochastic Approach (moisture content scenarios)**

**Economic objective (Minimization of total annual cost)**

**Production costs**

The amount of biomass cultivation is not affected by the moisture content; therefore, the production cost can be assessed based on the following formulas (173-174):

\[
PC = \sum_{i=1}^{I} ALC_i \times C_{production} \tag{173}
\]

\[
ALC = \sum_{i=1}^{I} Acrelease_i \times PP_i \tag{174}
\]
Harvesting Cost
The harvesting cost based on each moisture content scenarios can be determined by the following equations (175-176):

\[
HC = [\sum_{e=1}^{E} (FC_e \times H_e) + \sum_{e=1}^{E} \sum_{t=1}^{T} (VCH_e \times H_e \times NAHWH_t)] + \\
[\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{e=1}^{E} \sum_{k=1}^{K} (TBH_{itk} \times HVcost_e \times \delta_k \times PbMC_k \times H_e)]
\] (175)

\[
TBH = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{k=1}^{K} ALC_i \times PP1_{it} \times YADJ_t \times YIELD_{itk}
\] (176)

Collecting costs
The total collection units cost under each moisture content scenarios can be defined by the following formulas (177-178):

\[
CC = [\sum_{m=1}^{M} (FC_m \times C_m) + \sum_{m=1}^{M} \sum_{t=1}^{T} (VC_m \times C_m \times NACWH_t)] + \\
[\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{k=1}^{K} (TBCol_{itk} \times CLcost_m \times \phi_k \times PbMC_k \times C_m)]
\] (177)

\[
TBCol = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{k=1}^{K} TBH_{itk}
\] (178)

Inventory costs
The cost of inventory under each moisture content scenarios can be determined by the following equation (179):

\[
IC = [\sum_{j=1}^{J} PriceSl_j \times Areal_j \times CRFStructure] + \\
[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{t \in S_1} (TBTSIR_{ijrk,ts} \times VCS_j \times PSI_{ts} \times \omega_k \times PbMC_k)] + \\
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{t \in S_1} (TBTSIR_{ijrk,ts} \times cost_{draying} \times EVRate_k \times \omega_k \times PbMC_k)]
\] (179)

In-field storage cost (INFSC)
The amount of in-field storage cost under each moisture content scenarios can be defined by the following formula (180):

86
\[ \text{INFSC} = \text{Fixed cost} + \text{Variable cost} = \left( \sum_{f=1}^{F} (\text{PriceINF} \ast \text{AreaINF}_f \ast \text{CRFINS}) \right) + \left( \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{w=1}^{W} \sum_{k=1}^{K} \sum_{t \in S_2} (T \text{BTSFRI}_frk,tsw \ast \theta_k \ast \text{PbMC}_k \ast \text{VCINF}_f \ast \text{PSF}_ts) \right) \]

**Transportation costs**

The amount of transportation unit cost under each moisture content scenarios can be determined by the following equations (181-183).

\[ \text{Transportation cost} = \sum_p^P [FC_p + VC_p] \ast TRN_p + \left( \sum_t^T \sum_p^P \sum_k^K \left[ \frac{BP_{tk}}{\text{loadMass}_{\text{loader}}} \ast L_{\text{loader}} * (FC_p \ast TRN_p) \right] \right) \]

\[ VCT_p = \left[ \left( \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{t \in S_1} T \text{BTSIR}_{ijrkt} \ast \beta_k \ast \text{PbMC}_k \ast (D_{ij} + D_{fr}) \ast \text{VC}_p \right) + \left( \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{t \in S_2} T \text{BTSFRI}_{frk} \ast \beta_k \ast \text{PbMC}_k \ast (D_{if} + D_{fr}) \ast \text{VCT}_p \right) \right] \]

\[ T_{\text{Transporter}} = \sum_p^P [FC_p + VC_p] \ast TRN_p \]

**Penalty cost on moisture content limit of feedstock**

The amount of penalty cost under each moisture content scenarios can be calculated by the following equation (184):

\[ \text{PCMC} = \left( \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{t \in S_1} T \text{BTSIR}_{ijrkt} \ast \beta_k \ast \text{PbMC}_k \ast (MCi - 15\%) \right) + \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{t \in S_2} T \text{BTSFRI}_{frk} \ast \beta_k \ast \text{PbMC}_k \ast (MCF - 15\%) \]
Supply constraints
The amount of land under cultivation based on each moisture content scenarios can be determined by the following formulas (185-186):

\[
ALC = \sum_{i=1}^{l} \sum_{k=1}^{K} Acrease_i \times PP_i \times \gamma_k \times PbMC_k
\]  
\[\text{Acrease}_i \leq ACRELAND_i, \forall (i) \]  
(185)

(186)

Harvesting constraint
The constraints regarding harvesting process under each weather scenarios are defined in the following equations (187-189):

\[
ALH = \sum_{i=1}^{l} \sum_{t=1}^{T} \sum_{k=1}^{K} ALC_{ik} \times PP_{1it}
\]  
(187)

\[
TBH = \sum_{i=1}^{l} \sum_{t=1}^{T} \sum_{k=1}^{K} ALC_{ik} \times PP_{1it} \times YADJ_t \times YIELD_{ik} \times \delta_k \times PbMC_k
\]  
(188)

\[
NAHW_H_t \leq Length_t, \forall (t)
\]  
(189)

Collecting constraint
The constraints regarding collection process can be found in the following equations (190-194):

\[
TBCol_{ifrkt} = TBH_{itk} = PD_{itk}, \forall (i, j, f, r, k, ts)
\]  
(190)

\[
TBCol = \sum_{i=1}^{l} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{ts \in S_1} (TBTSIR_{ijrk,t} \times \beta_k \times PbMC_k) + \sum_{i=1}^{l} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{ts \in S_2} (TBTSFR_{ifrkt} \times \beta_k \times PbMC_k)
\]  
(191)

\[
NACWH_{t} \leq Length_{t}, \forall (t)
\]  
(192)

\[
PD_{contracted} = \sum_{i=1}^{l} \sum_{t=1}^{T} \sum_{k=1}^{K} BP_{ltk}
\]  
(193)
\[ \text{BP} = \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{k=1}^{K} \text{Acrelease}_i \times \text{PP}_t \times \text{YADJ}_t \times \text{Yield}_i \times \alpha_k \times \text{PbMC}_k \]  

(194)

**In-field storage constraint**

The constraint regarding the in-field storage site under each moisture content scenarios is defined by the following constrain (195):

\[ \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{r=1}^{R} \text{TBTSFR}_{ifr{k},ts} \leq \text{CAPINF}_f , \forall (f, ts \in S_2, k) \]  

(195)

According to the following equation (196) the total amount of biomass transferred to the inventory or in-field storage site under each moisture content scenarios is equal to the biomass produced at each time period.

\[ \sum_{s:(0,s) \in S_2} \text{TBTSFR}_{ifr{k},0s} \times \text{PbMC}_k + \sum_{s:(0,s) \in S_2} \text{TBTSIR}_{ifr{k},0s} \times \text{PbMC}_k = \text{BP}_{l0k} \times \alpha_k \times \text{PbMC}_k , \forall (i, f, j, r, t, k) \]  

(196)

**Storage constraint**

\[ \sum_{i=1}^{I} \sum_{r=1}^{R} \text{TBTSIR}_{ijrk,ts} \times \text{PbMC}_k \leq \text{CAPI}_j , \forall (j, ts \in S_1, k) \]  

(197)

Storage capacity should be between its lower and upper bounds:

\[ \text{LBI}_j \leq \text{UBI}_j \leq \text{CAPI}_j , \forall (j) \]  

(198)

The total inventory of all the feedstocks in terms of volume should not exceed the designed storage capacity:

\[ \sum_{i=1}^{I} \sum_{r=1}^{R} \frac{\text{TBTSIR}_{ijrk,ts} \times \text{PbMC}_k}{(1-\text{MCI}) \times \text{Dens}} \leq \text{PCapI}_j , \forall (j, ts \in S_1, k) \]  

(199)

**Transportation constraint**

Based on the following constraints (200-203), the amount of biomass transferred by each transportation unit under each moisture content scenarios are limited by the weight and volume capacity of transportation units.
\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \frac{TBTSIR_{ijk,ts} \cdot PbMC_k}{(1-MC_k) \cdot Dens} \leq VICT \quad \forall (ts \in S_1, k) 
\] (200)

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \frac{TBTSIR_{ijk,ts} \cdot PbMC_k}{(1-MC_k)} \leq WCT \quad \forall (ts \in S_1, k) 
\] (201)

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \frac{TBTSFR_{ijk,ts} \cdot PbMC_k}{(1-MC_k) \cdot Dens} \leq VICT \quad \forall (ts \in S_2, k) 
\] (202)

\[
\sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \frac{TBTSFR_{ijk,ts} \cdot PbMC_k}{(1-MC_k)} \leq WCT \quad \forall (ts \in S_2, k) 
\] (203)

**Demand constraint**

Based on the equation (204), the amount of biomass transferred to the biorefinery under each moisture content scenarios should be equal to the biorefinery demand at each time period.

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{t: (t,s) \in S_1} TBTSIR_{ijk,ts} \cdot PbMC_k + \\
\sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{t: (t,s) \in S_2} TBTSFR_{ijk,ts} \cdot PbMC_k = DEM_s \quad \forall (s, k) 
\] (204)

**Binary variable constraint**

\[
\sum_{e=1}^{E} H_e - 1 = 0 ; \sum_{m=1}^{M} C_m - 1 = 0 ; \sum_{p=1}^{P} TRN_p - 1 = 0 
\] (205)

\[
H_1 = C_1 \quad ; \quad H_2 = C_2 \quad ; \quad H_3 = C_3 \quad ; \quad TRN_1 = H_1 \quad ; \quad TRN_2 = H_2 + H_3 
\] (206)

**Logical constraint**

All the variables should be non-negative.

6.6 Simulation model

To show the workability and timeliness of the green biomass logistics, a simulation model was defined regarding the requirements of the system. Therefore, all the information related to the previous three objective functions were used to develop a simulation model like the real-world
condition. In this study, at first, a general information about simulation modeling is presented and then the modeling part is described in detail (Zhang, Johnson and Johnson, 2012).

6.6.1 Modeling and Simulation
Modeling and simulation can be defined as a process of applying physical, mathematical or logical models to demonstrate a real system, entity, event or a kind of process. Modeling and simulation as a useful tool can be applied to run a complicated system over a long time and obtain statistical results based on the dynamic situations of the system. Furthermore, modeling and simulation can purpose valuable information which is applicable in technical decision making (Zhang, Johnson and Johnson, 2012).

Activity Model
The activity model provides a graphical representation of the model which aids to better describe different activities and processes belongs to a certain model. In this study, in order to show the relationships between different stages of biomass logistics, an Integrated Definition (or IDEF) was applied to better depict the inputs, outputs, controls, mechanisms, and metrics used in the model (Hanrahan, 1995). Different activities and steps in the biomass logistics which is applied in the model is illustrated in the following figures (14-28).

6.6.2 Simulation model design
The development of biomass logistics for transferring feedstocks from a source site to a biorefinery has several key activities and processes such as biomass cultivation, harvesting, collecting, transporting feedstocks from field to inventory and storing them into the inventory and then transporting feedstocks from in-field storage sites or inventories to the biorefinery site.

By applying the simulation model, it is possible to evaluate the logistics of biomass regarding multiple principles including the delivered feedstock costs, energy consumption, and GHG emissions (Zhang, Johnson and Johnson, 2012). The delivered feedstock costs, as stated earlier, consists of cultivation cost, harvesting/collecting cost, storage cost and transportation cost (including loading and unloading costs). It was assumed that energy use and GHG emissions are
associated with each biomass logistics activities. The simulation model was built using Arena Simulation Software (Arena simulation software, 2017).

In the following figure, the entire logistics of biomass to biorefinery is depicted. Among the main input parameters in the simulation model we can mention the following items such as the amount of energy consumption, biomass characteristics such as yield, economic parameters, and so on. A complete list of input parameters in each step is presented in the following figures.

![Diagram](image)

Figure 14: The overall activity model for biomass logistics

![Diagram](image)

Figure 15: Cultivation activity
Figure 16: Harvesting activity

Figure 17: Collecting activity
Figure 18: Forwarding to in-field storage site

Figure 19: Loading at in-field storage site
Figure 20: Transportation to inventory activity

Figure 21: Unload at inventory activity
Figure 22: Store at inventory activity

Figure 23: Loading at inventory activity
Figure 24: Transportation to biorefinery activity

Figure 25: Storing at in-field storage activity
Figure 26: Loading at in-field storage site activity

Figure 27: Transport to biorefinery activity
Figure 28: Storing at biorefinery activity

**Sub-models**

The simulation model consists of six sub-models. The first three sub-models related to the different harvesting and collecting system, the next two sub-models which split the flow of materials to inventory and in-field storage sites and the last one relates to the biorefinery storage.

Figure 29: Bailing system sub-model

Figure 30: Ensiling system sub-model
Figure 31: Chopping system sub-model

Figure 32: Storage in Inventory and transport to biorefinery

Figure 33: Storage in In-field storage and transport to biorefinery
Figure 34: Storage in biorefinery

Figure 35: Total model include all sub-models
The optimization and simulation models were combined in order to provide more precise solution for the biomass logistics problem. The algorithm here is, at first the model requires the user to enter the entity data into the model via the interface forms, which depicted in the following parts. After that, based on the entry data the optimization model provides the optimum values for the three predefined objectives functions. Based on the results from optimization model and entry data, the simulation model applied to determine the workability and timeliness of the processes. The interface form designed based on the spreadsheet excel software, which integrate the Lingo and Arena simulation software to make an integrated assessment tool.

Figure 36: Schematic of assessment tool
7.1 Cultivation form
In the first form, user should enter all the required information for cultivation process and after filling all required parts, it could be possible to register the information in the database for further calculation.

Figure 37: Cultivation form

7.2 Harvesting/collecting form
The required information for harvesting and collecting process is entered in this form. This form includes three sub-pages, which enables user to select the preferred harvesting or collecting systems based on the suggestion of the tool or by user selection.
Figure 38: Harvesting/Collecting form1
Figure 39: Harvesting/collecting form 2
7.3 Storing information form

This form enables user to input the required information for storing process. After completing all parts, it could be possible to register the latest information in the database.

![Storing information form](image)

Figure 40: Storing information form
7.4 Transporting information form
The last form depicts the required information for the transportation process. After filling the information by the user, the process of data entry is finished and the optimization model could be run based on the inputs.

Figure 41: Transporting information form
8 RESULTS AND DISCUSSION

8.1 Solving Multi-Objective Problem by applying Fuzzy Programming Method

Fuzzy programming method as a useful tool for dealing with uncertainties and complexities, is a simplification of traditional set theory which is introduced for the first time by Zadeh in 1965. This method has been successfully applied by Bellman and Zadeh (Bellman and Zadeh, 1970) in order to solve various kinds of multi-objective problems. A fuzzy set is associated with its membership function which is defined from its elements to the interval [0,1] plays a key role in solving multi-objective decision making problems. As there are several types of fuzzy membership functions, a suitable membership function is to be selected to solve the real world multi-objective mathematical programming problems. Defining a fuzzy membership function $\mu_k(x)$ for the $K^{th}$ objective function $f^k_0(x)$ is as follows:

$$
\mu_k(x) = \begin{cases} 
1 & \text{if } f^k_0(x) \leq L_k \\
\frac{u_k-f^k_0(x)}{u_k-L_k} & \text{if } L_k \leq f^k_0(x) \leq U_k \\
0 & \text{if } f^k_0(x) \leq U_k
\end{cases}
$$

(207)

Where $L_k \neq U_k$, $k=1, 2, ..., p$ and $L_k, U_k$ are minimum and maximum values of the objective function respectively. If $L_k = U_k$, then we can define $\mu_k(x) = 1$ for any value of $K$.

Now we can define the membership function $\mu_k(x)$, $K=1, 2, ..., p$ subject to the constraints $g_i(x) \leq 1$ and $x_j \geq 0$, $j = 1, 2, ..., n$ and then use a max-min operator to find a crisp model. A dummy variable $\theta$ is considered and a crisp model for fuzzy programming problem is formulated as follows:

$max: \theta$

subject to: $\frac{u_k-f^k_0(x)}{u_k-L_k} \geq \theta$, $k = 1, 2, ..., p$

$g_i(x) \leq 1$, $i = 1, 2, ..., m$

$\theta \geq 0$, $x_j > 0$, $j = 1, 2, ..., n$
Furthermore, the inequality can be represented as follows:

\[ f_{0}^{(k)}(x) + (U_k - L_k)\theta \leq U_k, \quad k = 1, 2, ..., p \]  

(209)

Now we can solve the crisp programming problem using the main objective function to find \( x^\ast \) and evaluate all \( p \) number of objective functions at this optimal solution \( x^\ast \).

To solve this problem based on this method, at first, we need to define the membership function for each objective functions. Therefore, we need to calculate the maximum and minimum values of each objective function.

The minimum value of first objective function is termed by \( L_1 = 93846.25 \) and the maximum amount is equal to \( U_1 = 313752.9 \), now we define the membership function as follows:

\[
\mu_1(x) = \begin{cases} 
1 & \text{if } f_{0}^1(x) \leq L_1 \\
\frac{u_1-f_{0}^1(x)}{u_1-L_1} & \text{if } L_1 \leq f_{0}^1(x) \leq U_1 \\
0 & \text{if } f_{0}^1(x) \leq U_1
\end{cases}
\]  

(210)

The same method can be used for the second objective function to obtain the second membership function; therefore, we have the minimum value of second objective function as \( L_2 = 1984757 \) and the maximum value as \( U_2 = 2432936 \), so we can define the membership function as follow:

\[
\mu_2(x) = \begin{cases} 
1 & \text{if } f_{0}^2(x) \leq L_2 \\
\frac{u_2-f_{0}^2(x)}{u_2-L_2} & \text{if } L_2 \leq f_{0}^2(x) \leq U_2 \\
0 & \text{if } f_{0}^2(x) \leq U_2
\end{cases}
\]  

(211)

Furthermore, we have \( L_3 = 25589910 \) as minimum value for the last objective function and \( U_3 = 26269970 \) as maximum amount. Therefore, we can define the membership function related to this objective function as follows:
\[
\mu_3(x) = \begin{cases} 
1 & \text{if } f_0^3(x) \leq L_3 \\
\frac{u_3 - f_0^3(x)}{u_2 - L_3} & \text{if } L_3 \leq f_0^3(x) \leq U_3 \\
0 & \text{if } f_0^3(x) \leq U_3
\end{cases}
\]  

(212)

Then we need to define the crisp model related to the three objective functions as follows:

\textbf{Max: } \theta

SubJECTED to:

\begin{align*}
& f_0^1(x) + (U_1 - L_1) * \theta \leq U_1 \\
& f_0^2(x) + (U_2 - L_2) * \theta \leq U_2 \\
& f_0^3(x) + (U_3 - L_3) * \theta \leq U_3 \\
& g_i(x) \leq 1, \ i = 1,2, \ldots m \\
& \theta \geq 0, \ x_j > 0, \ j = 1,2, \ldots n
\end{align*}

(213)

The defined crisp model solved in the Lingo software and the optimum amount of \( \theta \) is equal to \( \theta^* = 0.8672519 \). To find the optimum amount of each objective functions, the amount of \( \theta^* \) should be put in the following formulae:

\begin{align*}
& f_1^*(x) = U_1 - (U_1 - L_1) * \theta^* = 123038.44 \\
& f_2^*(x) = U_2 - (U_2 - L_2) * \theta^* = 2044251.91 \\
& f_3^*(x) = U_3 - (U_3 - L_3) * \theta^* = 25680186.67
\end{align*}

(214)

Therefore, based on the results, the optimum amount of all three objective functions are as follow. The optimum value regarding cost function is 123038.44$ and this amount is equal to 2044251.91 (kg. Co₂) for second objective function and the optimum value regarding the last objective function is equal to 25680186.67 (MJ).
8.2 Results weather scenarios

In this work, the second scenario is considered as a base scenario. The input values regarding the base scenario is gained from tables which presented in the part 3. The model is solved for the base scenario (2nd scenario) and the obtained results is presented in table 29.

Table 29: Modeling results for base scenario

<table>
<thead>
<tr>
<th>Model Variables</th>
<th>Values</th>
<th>Model Variables</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>NLOADER</td>
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</table>

By applying all scenarios in the model, numerous type of information can be compared based on each defined scenario. For instance, here, the amount of biomass which transferred through time periods under each weather scenario was considered.

Feedstocks can be transfer in to biorefinery from two ways, first, from the inventory site and second, from in-field storage site. The timetable of transportation and the amount of shipment based on the type of inventory was showed in the tables [30-37].
Source site – Inventory – Biorefinery

It should be considering that the weather factors are not affected the amount of biomasses which transferred to the inventory site because in this type of storage the feedstocks are protected in a covered area. Therefore, there is no change in the amount of this variable regarding each weather scenarios.

Table 30: Quantity of biomass (ton) which transferred from source site to the Inventory site and then transferred to biorefinery at each time period under weather scenario 1

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<th>AUG</th>
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</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
</tr>
</tbody>
</table>

Table 31: Quantity of biomass (ton) which transferred from source site to the Inventory site and then transferred to biorefinery at each time period under weather scenario 2

<table>
<thead>
<tr>
<th></th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBTSIR-S2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JUN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>JUL</td>
<td>0</td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
<td>0</td>
</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
</tr>
</tbody>
</table>

Table 32: Quantity of biomass (ton) which transferred from source site to the Inventory site and then transferred to biorefinery at each time period under weather scenario 3

<table>
<thead>
<tr>
<th></th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBTSIR-S3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
<td>0</td>
</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
</tr>
</tbody>
</table>

Table 33: Quantity of biomass (ton) which transferred from source site to the Inventory site and then transferred to biorefinery at each time period under weather scenario 4

<table>
<thead>
<tr>
<th></th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBTSIR-S4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>JUL</td>
<td>0</td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
<td>0</td>
</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>180.75</td>
</tr>
</tbody>
</table>
Source site - In-field storage – Biorefinery

In the following tables the amount of biomass that should be sent to the biorefinery from in-field storage site in each time period is presented.

Table 34: Quantity of biomass (ton) which transferred from source site to the in-field storage site and then transferred to biorefinery at each time period under weather scenario 1

<table>
<thead>
<tr>
<th>TBTSFR-S1</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>596.25</td>
<td>0</td>
</tr>
<tr>
<td>JUL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>596.25</td>
<td>596.25</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>596.25</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 35: Quantity of biomass (ton) which transferred from source site to the in-field storage site and then transferred to biorefinery at each time period under weather scenario 2

<table>
<thead>
<tr>
<th>TBTSFR-S2</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>198.75</td>
<td>0</td>
</tr>
<tr>
<td>JUL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>198.75</td>
<td>198.75</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>198.75</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 36: Quantity of biomass (ton) which transferred from source site to the in-field storage site and then transferred to biorefinery at each time period under weather scenario 3

<table>
<thead>
<tr>
<th>TBTSFR-S3</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>149.0625</td>
<td>0</td>
</tr>
<tr>
<td>JUL</td>
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<td>0</td>
<td>0</td>
<td>149.0625</td>
<td>149.0625</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>149.0625</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 37: Quantity of biomass (ton) which transferred from source site to the in-field storage site and then transferred to biorefinery at each time period under weather scenario 4

<table>
<thead>
<tr>
<th>TBTSFR-S4</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>298.125</td>
<td>0</td>
</tr>
<tr>
<td>JUL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>298.125</td>
<td>298.125</td>
</tr>
<tr>
<td>AUG</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>298.125</td>
</tr>
<tr>
<td>SEP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OCT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

113
The amount of biomass which transferred to the biorefinery at each time period should be equal to the demand at that time. In this study, we consider a demand of 300 ton for each month. For instance, in the first scenario, we have:

\[
\text{DEM(JUL)} = \text{TBTSIR(JUN-JUL)} + \text{TBTSIR(JUL-JUL)} = 0 + 300 = 300
\]
\[
\text{DEM(AUG)} = \text{TBTSIR(JUN-AUG)} + \text{TBTSIR(JUL-AUG)} + \text{TBTSIR(AUG-AUG)} = 0 + 0 + 300 = 300
\]
\[
\text{DEM(SEP)} = \text{TBTSFR(JUN-SEP)} \times \text{Pb(w)} + \text{TBTSFR(JUL-SEP)} \times \text{Pb(w)} + \text{TBTSIR(AUG-SEP)} + \text{TBTSIR(SEP-SEP)} = 596.25 \times 0.1 + 596.25 \times 0.1 + 0 + 180.75 = 300
\]
\[
\text{DEM(OCT)} = \text{TBTSFR(JUL-OCT)} \times \text{Pb(w)} + \text{TBTSFR(AUG-OCT)} \times \text{Pb(w)} + \text{TBTSIR(OCT-OCT)} = 596.25 \times 0.1 + 596.25 \times 0.1 + 180.75 = 300
\]

Figure 42: Quantity of biomass shipment based on each scenario

According to the results, the model purposes chopping system as the best method for harvesting and collecting (H3=1, C3=1). Furthermore, pile truck is selected as the best method for transportation (TRN2=1). Moreover, the model assessed the proper number of farm machineries for harvesting and collecting. In this regard, 2 loaders, 1 forage harvester, 2 forage wagons and 2 forage tractors is considered as harvesting/collecting units. Based on the results that depicted in figure 42, the first scenario has the lowest amount of cost among other scenarios. If we compare
this scenario with the base scenario, the total amount of production in the first scenario is equal to 12000 ton which is more than amount of biomass that produced in the base scenario (4706 ton). If we consider the third scenario, the amount of production is slightly lower than the base scenario (3158 ton) but the amount of objective function regarding this scenario is more than base scenario because the probability of occurrence for third scenario is more than second one. Finally, in the last scenario, the amount of total production is (7430 ton) which is more than base scenario but the amount of objective function regarding this scenario is lower than the base scenario due to the lower amount of probability of occurrence.

8.3 Results moisture content scenarios

In this study, in order to deal with uncertainties regarding moisture content of biomass, four different scenarios were defined to examine different conditions in the system. The second scenario is defined as a base scenario. Therefore, we are going to compare other scenarios based on it. The results regarding the base scenario is demonstrated in the following table (43).
Table 38: Results of base scenario for moisture content

<table>
<thead>
<tr>
<th>Model Variables</th>
<th>Values</th>
<th>Model Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLOADER</td>
<td>2</td>
<td>TRN2</td>
<td>1</td>
</tr>
<tr>
<td>NWINDROWER</td>
<td>0</td>
<td>TBTSIR(JUN-JUL)</td>
<td>0</td>
</tr>
<tr>
<td>NRAKER</td>
<td>0</td>
<td>TBTSIR(JUN-AUG)</td>
<td>0</td>
</tr>
<tr>
<td>NBALER</td>
<td>0</td>
<td>TBTSIR(JUN-SEP)</td>
<td>0</td>
</tr>
<tr>
<td>NCOMBINE</td>
<td>0</td>
<td>TBTSIR(JUL-JUL)</td>
<td>1052.63</td>
</tr>
<tr>
<td>NFORAGE_HARVESTER</td>
<td>1</td>
<td>TBTSIR(JUL-AUG)</td>
<td>0</td>
</tr>
<tr>
<td>NSILAGEWAGON</td>
<td>0</td>
<td>TBTSIR(JUL-SEP)</td>
<td>0</td>
</tr>
<tr>
<td>NSILAGETRACTOR</td>
<td>0</td>
<td>TBTSIR(AUG-AUG)</td>
<td>1052.63</td>
</tr>
<tr>
<td>NFORAGEWAGON</td>
<td>2</td>
<td>TBTSIR(AUG-SEP)</td>
<td>0</td>
</tr>
<tr>
<td>NFORAGETRUCTOR</td>
<td>0</td>
<td>TBTSIR(SEP-SEP)</td>
<td>0</td>
</tr>
<tr>
<td>NBALERTRACTOR</td>
<td>0</td>
<td>TBTSIR(OCT-SEP)</td>
<td>0</td>
</tr>
<tr>
<td>NTRUCKSEMITRAILER</td>
<td>0</td>
<td>TBTSFR(JUN-SEP)</td>
<td>0</td>
</tr>
<tr>
<td>NTRUCK</td>
<td>1</td>
<td>TBTSFR(JUN-OCT)</td>
<td>0</td>
</tr>
<tr>
<td>ACRELEASE</td>
<td>102.041</td>
<td>TBTSFR(JUL-OCT)</td>
<td>0</td>
</tr>
<tr>
<td>CAPI</td>
<td>700.692</td>
<td>TBTSFR(AUG-OCT)</td>
<td>1052.63</td>
</tr>
<tr>
<td>H1</td>
<td>0</td>
<td>PD(JUN)</td>
<td>0</td>
</tr>
<tr>
<td>H2</td>
<td>0</td>
<td>PD(JUL)</td>
<td>1669.18</td>
</tr>
<tr>
<td>H3</td>
<td>1</td>
<td>PD(AUG)</td>
<td>1669.18</td>
</tr>
<tr>
<td>C1</td>
<td>0</td>
<td>PP1(JUN)</td>
<td>0</td>
</tr>
<tr>
<td>C2</td>
<td>0</td>
<td>PP1(JUL)</td>
<td>0.5</td>
</tr>
<tr>
<td>C3</td>
<td>1</td>
<td>PP1(AUG)</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>PP1(SEP)</td>
<td>0</td>
</tr>
<tr>
<td>D1</td>
<td>9</td>
<td>PP1(OCT)</td>
<td>0</td>
</tr>
<tr>
<td>D2</td>
<td>1</td>
<td>PP1(JUL)</td>
<td>0.5</td>
</tr>
<tr>
<td>D3</td>
<td>9</td>
<td>PP1(AUG)</td>
<td>0.5</td>
</tr>
<tr>
<td>TRN1</td>
<td>0</td>
<td>PP1(SEP)</td>
<td>0</td>
</tr>
</tbody>
</table>

Based on the results, all four scenarios were compared according to three items, the value of objective function, acres of land required for cultivation and the amount of biomass production in each month. Table (39) demonstrates the information required for comparing scenarios.

Table 39: Value of objective function, required acres of land and biomass production in each scenario

<table>
<thead>
<tr>
<th>Variables</th>
<th>Scenario 1</th>
<th>Base scenario</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective function</td>
<td>85791</td>
<td>87911.2</td>
<td>86279.93</td>
<td>84329</td>
</tr>
<tr>
<td>ACRELEASE</td>
<td>102.041</td>
<td>102.041</td>
<td>102.041</td>
<td>102.041</td>
</tr>
<tr>
<td>PD(JUN)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PD(JUL)</td>
<td>2100.84</td>
<td>1669.18</td>
<td>2339.18</td>
<td>3921.57</td>
</tr>
<tr>
<td>PD(AUG)</td>
<td>2100.84</td>
<td>1669.18</td>
<td>2339.18</td>
<td>3921.57</td>
</tr>
<tr>
<td>PD(SEP)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PD(OCT)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
If we consider the first scenario, the amount of biomass production is more than the base scenario due to the higher rate of production factor which considered for this scenario. The amount of biomass that should be send to the biorefinery in the first scenario is more than the base scenario as a result of bigger transportation factor than base scenario. However, the amount of objective function regarding this scenario is lower than the base scenario due to the lower amount of probability regarding the occurrence of this scenario. In the third scenario, the amount of production is lower than the second scenario due to the lower production factor than base scenario. The amount of biomass transferred to the biorefinery is a bit more than the base scenario and the amount of objective function regarding this scenario lower than the base scenario. Finally, in the last scenario the amount of production is more than the base scenario and the amount of objective function regarding this scenario by considering the effect of all factors is lower than the base scenario. The following figure (44) depicted the amount of biomass transferred to the biorefinery based on each scenarios.
8.4 Sensitivity analysis

In this study, the biomass yield and the distance from source site to biorefinery was considered for sensitivity analysis.

8.4.1 Biomass yield

Several factors can affect the profits of biorefinery such as the type of biomass, yield, available field operation working hours, the capacity of biorefinery, the distance of field from biorefinery and so on. Biomass yield is a key factor in selection of biomass type in the system. The cost of biomass production, the machineries costs, the amount of GHG emissions and the amount of energy usage can increase because of selecting low yield biomass. The table 40 shows the amount of alteration in biomass production cost, the amount of GHG emission and energy consumption by variation in biomass yield.
Table 40: Sensitivity analysis for biomass yield

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>319473.7</td>
<td>2445551</td>
<td>26297520</td>
</tr>
<tr>
<td>4</td>
<td>317586</td>
<td>2441346</td>
<td>26288340</td>
</tr>
<tr>
<td>5</td>
<td>316453.3</td>
<td>2438823</td>
<td>26282830</td>
</tr>
<tr>
<td>6</td>
<td>315698.2</td>
<td>2437141</td>
<td>26279160</td>
</tr>
<tr>
<td>7</td>
<td>315158.9</td>
<td>2435940</td>
<td>26276530</td>
</tr>
<tr>
<td>8</td>
<td>314754.3</td>
<td>2435039</td>
<td>26274560</td>
</tr>
<tr>
<td>9</td>
<td>314439.7</td>
<td>2434338</td>
<td>26273030</td>
</tr>
<tr>
<td>10</td>
<td>314188</td>
<td>2433777</td>
<td>26271810</td>
</tr>
<tr>
<td>11</td>
<td>313982.1</td>
<td>2433318</td>
<td>26270810</td>
</tr>
<tr>
<td>12</td>
<td>313810.5</td>
<td>2432936</td>
<td>26269970</td>
</tr>
<tr>
<td>13</td>
<td>313665.2</td>
<td>2432613</td>
<td>26269270</td>
</tr>
<tr>
<td>14</td>
<td>313540.8</td>
<td>2432335</td>
<td>26268660</td>
</tr>
<tr>
<td>15</td>
<td>313432.9</td>
<td>2432095</td>
<td>26268130</td>
</tr>
<tr>
<td>16</td>
<td>313338.5</td>
<td>2431885</td>
<td>26267680</td>
</tr>
<tr>
<td>17</td>
<td>313255.2</td>
<td>2431699</td>
<td>26267270</td>
</tr>
</tbody>
</table>

The following figure (45) demonstrates the relations between changes in the value of biomass yield on all three objective functions.

Figure 45: The effect of yield variation on production and GHG emission biomass

8.4.2 Distance between source site and biorefinery

The distance of biomass source site from biorefinery as a crucial factor can influence the biomass production costs. By increasing the amount of this variable, the logistics costs can rise due to the
growing of transportation costs. Furthermore, the amount of environmental impacts can be influenced by the change of distance between field and biorefinery. Increasing the radius of distance from biorefinery can rise the amount of GHG emission produced by vehicles. Moreover, the amount of energy usage by the system increased due to the growth in amount of distance from biorefinery. In the table (41) all the information regarding the changes in the distance radius from biorefinery and the related alteration on all three objective functions is demonstrated.

Table 41: Variation in distance radius from biorefinery

<table>
<thead>
<tr>
<th>Distance (Km)</th>
<th>Cost ($)</th>
<th>Environmental impact (GHG emission)</th>
<th>Energy consumption (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>300230.9</td>
<td>1448916</td>
<td>13651170</td>
</tr>
<tr>
<td>6</td>
<td>301310.9</td>
<td>1645668</td>
<td>16123440</td>
</tr>
<tr>
<td>7</td>
<td>302390.9</td>
<td>1842420</td>
<td>18659040</td>
</tr>
<tr>
<td>8</td>
<td>303470.9</td>
<td>2039172</td>
<td>21194640</td>
</tr>
<tr>
<td>9</td>
<td>304550.9</td>
<td>2235924</td>
<td>23730240</td>
</tr>
<tr>
<td>10</td>
<td>305630.9</td>
<td>2432676</td>
<td>26265840</td>
</tr>
<tr>
<td>11</td>
<td>306710.9</td>
<td>2629428</td>
<td>28801440</td>
</tr>
</tbody>
</table>

Figure (46) depicted that how alteration in the value of distance between biorefinery and field can affects the values regarding all objective functions.

![Distance (Field-Biorefinery) Km](image)

Figure 46: The effect of distance variation on production and GHG emission biomass
8.4.3 Sensitivity analysis by considering four factors

In this part, we consider four important factors that significantly affect the cost objective function. Therefore, we select the number of harvesting working hours, the distance between source site and biorefinery site, the amount of biomass yield and the amount of moisture content of feedstocks for this investigation. We assume a range of values regarding each factor. The related information is demonstrated in the following table (42).

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of working hours</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Distance</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Biomass yield</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>15.00%</td>
<td>25.00%</td>
</tr>
</tbody>
</table>

The model runs based on the different possible values for each mentioned factors between defined ranges. The results from this calculation was also modeled in order to find a relation between these factors and cost objective function. For instance, in the following figure (47), the interaction between two factors, biomass yield and distance is depicted. According to the figure, we can conclude that in the fixed distance value if the amount of biomass yield increase then the amount of cost decreases. Furthermore, in the fixed value of biomass yield, by rising the value of distance, we will see the increase in the amount of cost. In order to gain minimum cost regarding these factors, we need to use higher yield biomasses and lease the land for production in distances near the biorefinery.
Figure 47: Relationship between biomass yield and distance and the effects of them on Cost.
REFERENCES
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Gebreslassie, B.H., Yao, Y. and You, F. 2012. Design under uncertainty of hydrocarbon biorefinery supply chains: multi objective stochastic programming models, decomposition


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APPENDICES

Economic objective (Minimization of total annual cost)

\[
\text{Min: } (\sum_{i=1}^{I} ALC_i \cdot CProductin) + \left( [\sum_{e=1}^{E} (FC_e \cdot H_e) + \sum_{e=1}^{E} \sum_{t=1}^{T} (VCH_e \cdot H_e \cdot NWHH_t)] + \right. \\
\left. [\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{e=1}^{E} (TBH_{lt} \cdot HV\text{cost}_e \cdot H_e)] + \right. \\
\left. ([\sum_{m=1}^{M} (FC_m \cdot C_m) + \sum_{m=1}^{M} \sum_{t=1}^{T} (VCH_m \cdot C_m \cdot NACWHH_t)] + [\sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{m=1}^{M} TBCol_{lt} \cdot \right. \\
\left. CL\text{cost}_m \cdot C_m]) + \right. \\
\left. ([\sum_{j=1}^{J} PriceSi_j \cdot Areal_j \cdot CRFStructure] + [\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_1} (TBTSIR_{ijr,ts} \cdot VCS_j \cdot ight. \\
\left. PSI_{ts}) + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_1} (TBTSIR_{ijr,ts} \cdot cost\_drying \cdot EVRate)])] + \right. \\
\left. \left( [\sum_{f=1}^{F} (PriceINF \cdot AreaINF_f \cdot CRFINF)] + [\sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{tS\in S_2} (TBTSFR_{ifr,ts} \cdot ight. \\
\left. VCINF_f \cdot PSF_{ts})]\right)\right) + \right. \\
\left. (TC\_transporters + Loading and unloading cost) + \right. \\
\left. ([\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_1} TBTSIR_{ijr,ts} \cdot (MCI - 15\%) + \sum_{i=1}^{I} \sum_{f=1}^{F} \sum_{r=1}^{R} \sum_{tS\in S_2} TBTSFR_{ifr,ts} \cdot ight. \\
\left. (MCF - 15\%)] \cdot PenaltyCost) \right). \right.
\]

Second objective function (Min Environmental impact)

\[
\text{min: } (\sum_{i=1}^{I} \sum_{t=0}^{T} (f_{iBP_t} \cdot Arealease_t \cdot PP_{lt} \cdot YADJ_t \cdot BYIELD_{i})) + \right. \\
\left. (\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_1} (f_{jBS_t} \cdot TBTSIR_{ijr,ts} \cdot PSI_{ts}) + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_2} (f_{jBS_t} \cdot ight. \\
\left. TBTSFR_{ifr,ts} \cdot PSF_{ts}) + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_1} (f_{jBS_t} \cdot TBTSIR_{ijr,ts} \cdot PSI_{ts}) + \right. \\
\left. \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_2} (f_{jBS_t} \cdot TBTSFR_{ifr,ts} \cdot PSF_{ts}) \right) + \right. \\
\left. \left( [\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_1} (f_{ijBT_t} \cdot TBTSIR_{ijr,ts} \cdot (D_{ij} + D_{jr} \cdot \tau_{ir})) + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{tS\in S_2} (f_{ijBT_t} \cdot TBTSFR_{ifr,ts} \cdot (D_{if} + ight. \\
\left. D_{fr} \cdot \tau_{ir}))\right) \right). \right.
\]

133
Third objective function (Max Efficiency)

\[
\min: \left( \sum_{i=1}^{l} \text{Acrelease}_i \cdot PP_i \cdot ECP \right) + \left( \sum_{t=1}^{l} \sum_{i=1}^{T} ALC_i \cdot PP_{1it} \cdot YADJ_t \cdot BYIELD_i \cdot ECH \right) + \left( \sum_{i=1}^{l} \sum_{t=1}^{T} ALC_i \cdot PP_{1it} \cdot YADJ_t \cdot BYIELD_i \cdot ECC \right) + \left( \sum_{i=1}^{l} \sum_{j=1}^{I} \sum_{r=1}^{R} \sum_{ts} \sum_{S_1} TBTSIR_{ijr,ts} \cdot PSI_{ts} \cdot ECSI \right) + \left( \sum_{i=1}^{l} \sum_{j=1}^{I} \sum_{r=1}^{R} \sum_{ts} \sum_{S_2} TBTSFR_{ifr,ts} \cdot PSF_{ts} \cdot ECSINF \right) + \left( \sum_{i=1}^{l} \sum_{j=1}^{I} \sum_{r=1}^{R} \sum_{ts} \sum_{S_1} TBTSIR_{ijr,ts} \cdot TBTSFR_{ifr,ts} \cdot DisIR \cdot ECT \right)
\]

Weight capacity and volume capacity of each transporter

\[
WCT1 = WC_{\text{semi-truck/trailer}} \cdot Ntrips = 30(\text{ton}) \cdot 90 \cdot 5 = 13500 \text{ (ton for 5 months)}
\]

\[
WCT2 = WC_{\text{truck}} \cdot Ntrips = 25(\text{ton}) \cdot 90 \cdot 5 = 11250 \text{ (ton for 5 months)}
\]

\[
VlCT1 = VlC_{\text{semi-truck/trailer}} \cdot Ntrips = 95(\text{m}^3) \cdot 90 \cdot 5 = 42750(\text{m}^3 \text{ for 5 months})
\]

\[
VlCT2 = VlC_{\text{truck}} \cdot Ntrips = 90(\text{m}^3) \cdot 90 \cdot 5 = 40500(\text{m}^3 \text{ for 5 months})
\]

Expected number of trips for transportation unit

\[
Ntrips = Ntrips1 + Ntrips2 = 30 + 60 = 90 \text{ (per month)}
\]

\[
Ntrips1 = \frac{\text{working hours}}{\text{cycle time}_1} \cdot \text{Length period} = 30
\]

\[
Ntrips2 = \frac{\text{working hours}}{\text{cycle time}_2} \cdot \text{Length period} = 60
\]
cycle time\(_1\) = 0.5h + 1h + 0.5h + 0.5h + 1h + 0.5h + 2h = 6h \hspace{1cm} (222)

cycle time\(_2\) = 0.5h + 2h + 0.5h + 2h = 5h \hspace{1cm} (223)

working hours = 10 (hours continuously) \hspace{1cm} (224)

\[
loadMass_{\text{loader}} = \left( LM_{\text{loader}} \times N_{\text{loading}} \right) \times \text{time periods} = (1(\text{ton}) \times 120) \times 1(\text{month}) = 120(\text{ton per month})
\]

\[
N_{\text{loading}} = (2 \times 30) + 60 = 120
\] \hspace{1cm} (226)
## Worksheet for Estimating Farm Machinery Costs

### Information

<table>
<thead>
<tr>
<th>Item</th>
<th>Tractor or power unit</th>
<th>Implement or attachment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine</td>
<td>180-hp. Tractor</td>
<td>25-foot Chisel Plow</td>
</tr>
</tbody>
</table>

A. Current list price of a comparable replacement machine

B. Purchase price or current used value of the machine

C. Accumulated hours to date (zero for a new machine)

D. Economic life, years of ownership remaining

E. Interest rate, % (cost of capital - inflation)

F. Field capacity, acres/hr. or tons/hr. *

G. Annual use, hours
   - For implement [Annual use, ________ acres / F]
   - ________ hr.
   - ________ hr.

H. Engine or PTO horsepower

I. Fuel price
   - $________/gal

### Estimating ownership costs

J. Remaining value [% from Table 1 x A]

K. Total depreciation [B - J]

L. Capital recovery factor (from Table 2)

M. Capital recovery [(K x L) + (E x J)]

N. Taxes, insurance, and housing [0.01 x ((B + J) / 2)]

O. Total ownership cost per year [M + N]

P. Ownership cost/hour [O / G]

### Estimating operating costs

Q. Total accumulated hours at end of life [(D x G) + C]

R. From Table 3, current repair % and % at end of life
   - current % end of life % current % end of life %

S. Total accumulated repairs
   - [% end of life - % current] x A]

T. Average repair cost/hour
   - [S / (G - C)]

U. Fuel cost/hour [0.044 (diesel) or 0.06 (gasoline) x H x I]

V. Lubrication cost/hour [0.15 x U]

W. Labor cost/hour [1.1 x wage rate $_________ / hr.]

X. Total operating cost/hour [T + U + V + W]

### Estimating total machinery costs

Y. Total cost/hour [(P + X)

Z. Total cost/hour for tractor and implement combined
   - Total cost/acre or ton [Z / F]

---

Figure 48: Worksheet for estimating farm machinery costs (Edwards, 2015)