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A Simulation Model of the “Bio-depot” Concept in the Context of Components of Variance and the “Taguchi Loss Function”

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To the Graduate Council:

I am submitting herewith a thesis written by Maximilian Platzer entitled "A Simulation Model of the “Bio-depot” Concept in the Context of Components of Variance and the “Taguchi Loss Function”." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

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A Simulation Model of the “Bio-depot” Concept in the Context of Components of Variance and the “Taguchi Loss Function”

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ABSTRACT

The research focuses on the simulation, statistical evaluation, costs, and continuous improvement of supply chains for bio-based materials. A significant challenge of using cellulosic feedstocks for biofuel or bioenergy production is the high per unit costs of final products, *e.g.,* biofuels. The goal of the research is to provide practitioners with useful statistical methods and a simulation Excel template for evaluating the variance and costs associated with the supply chain of bio-based products. Statistical Process Control (SPC), components of variance, Taguchi Loss Function, and reliability block diagrams (RBD) are used in this thesis for the evaluation of the supply chain system of handling the feedstock components for biofuel production. These statistical methods are well accepted and suitable to assess and monitor the components of the supply chain for biofuel feedstocks, *e.g.,* Switchgrass (*Panicum virigatum L.*), loblolly pine (*Pinus taeda L.)* chips, etc. Applying these statistical methods will allow for the quantification of the variance of the system and its components, *e.g.,* feedstock particle size processing, drying, and ash content. The overall goal of the study is to quantify the variation of the components within the supply chains, estimate components costs (and total cost) using the Taguchi Loss Function, and provide suggestions for improvement of the system (www.spc4lean.com).

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CHAPTER I. INTRODUCTION

Problem Identification and Explanation

Inspired by various oil crises in the 20th century, the relationship between economic growth and energy consumption has become a highly investigated topic in energy economics over the past 35 years for both developed and current developing countries (Sanderson *et al.*, 1996). The assumption of a correlation between economic growth and energy consumption arose from the first oil crisis in the 1970s and after-effect economic recessions (Ouédraogo, 2010). Mohsen Mehrara (2007) compared energy consumption and the gross domestic product (GDP) of 11 selected oil exporting countries. Findings of the study suggest that GDP is a driver for energy consumption, not vice versa. In other words economic growth was slower than energy consumption (Mehrara, 2007). Ozturk, Aslan, & Kalyoncuc (2010) analyzed energy data from 51 countries from 1971 to 2005 focusing on energy consumption and economic growth. The 51 countries were divided into three groups, namely, low-, middle-, and upper- income group. The empirical outcome of the study states that it is not possible to conclude a direct relation between energy consumption and economic growth. Nevertheless, studies identified a relationship between energy dependent countries and energy policies

due to the possible negative effect of a shortage in available energy on the national economy (Ozturk *et al.*, 2010).

United States politicians introduced the "Energy Independence and Security Act" (EISA) in 2007. This act is an energy policy law that focuses on provisions designed to increase energy efficiency as well as promoting the use of renewable energy in the U.S. Three key provisions enacted in the policy are the Corporate Average Fuel Consumption Standards (CAFE), the Renewable Fuel Standards (RFS), and the Appliance and Lightning Efficiency Standards (Sissine, 2007). RFS mandates that a certain percentage of transportation fuel used within U.S. borders must contain biofuel. The purpose of this standard is to diversify the energy portfolio of the U.S., promote energy independence, and strengthen rural economies. EISA acknowledges four types of renewable fuel divisions: conventional biofuel, cellulosic biofuel, advanced biofuel, and biomass-based diesel. Concerns arose among practitioners if the annual supply stated in EISA could be met by the biofuel industry (Bracmort, 2015). Biomass–derived transportation fuels and energy resources have been considered as an alternative to fossil fuels. Bioenergy development is widely supported by many governments throughout the world (Solecki *et al.*, 2013). More than 60 countries have developed biofuels policies, these policies are intended to promote markets for

biofuels with price support until such fuels become economically competitive (Figure 1) (Wilkinson 2013).

The idea of sustainability and renewability is important to the bioenergy/biofuel industry (Yue *et al.*, 2014). Producing energy from biomass feedstocks presents difficulties due to low density for transport, feedstock quality variation, production performance, and variation of supply. These factors are critical in the context of the biomass energy supply chain (Mafakheri *et al.*, 2014).

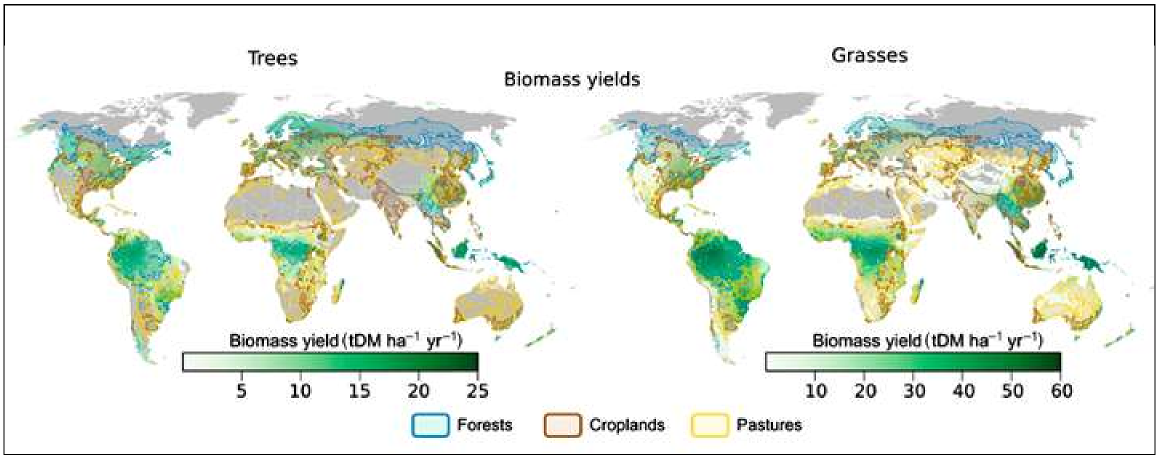

Figure 1. Simulated biomass yields for woody and herbaceous energy crops averaged from 1966-2005 (Berninger, 2011).

A company's business strategy involves leveraging competencies to achieve strategic goals. This competency directs the firm's theoretical performance direction. For example, in the context of this thesis, a functional and optimized supply chain focuses on the reduction of operational costs and maximization of efficiency (Happek, 2005).

The geographical scope of this thesis is the Southeastern United States. The regional focus is the result of the “Biofuels Strategic Production Report” by the U.S. Department of Agriculture in 2010. USDA projected that in the U.S., in order to meet the RFS goals by 2022, a combination of dedicated energy crops (perennial grasses, biomass sorghum, and energy cane), oilseeds (soy, canola), crop residues (corn stover, straw), woody biomass and corn starch will be necessary. The USDA estimated the contribution from different regions in the United States for biofuel production (Figure 2). Five geographical regions of the U.S. were categorized based on percentages regarding their contribution to the Renewable Fuel Standard 2 (RFS2). The current wood supply for biomass energy consists of 81 power generating biomass-based projects of which 51 produce wood, and 17 produce liquid biofuel (Sooduck, 2010). European Union (EU) countries have developed independent national renewable action plans presenting schedules and engagements to meet the EU’s Renewable Energy Directive (RED), by 2020 (Commission, 2009). RED foresees that at least 20% of total European energy consumptions will come from renewable fuels. Energy from renewable fuels may come from wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases (Parliament, 2008). Due to the high demand for wood pellets in the EU, especially driven by the United Kingdom, Belgium, Denmark, and Netherlands; wood pellet exports from U.S. have risen from 1.6 million short tons in 2012 to 3.2 million short tons in in 2013.

Ninety-eight percent of these exports were directly shipped to Europe (Wong *et al.*, 2014). In 2014, 73% of the 4.4 million short tons, exported by the U.S., were delivered to the United Kingdom (Lowenthal-Savy, 2015).

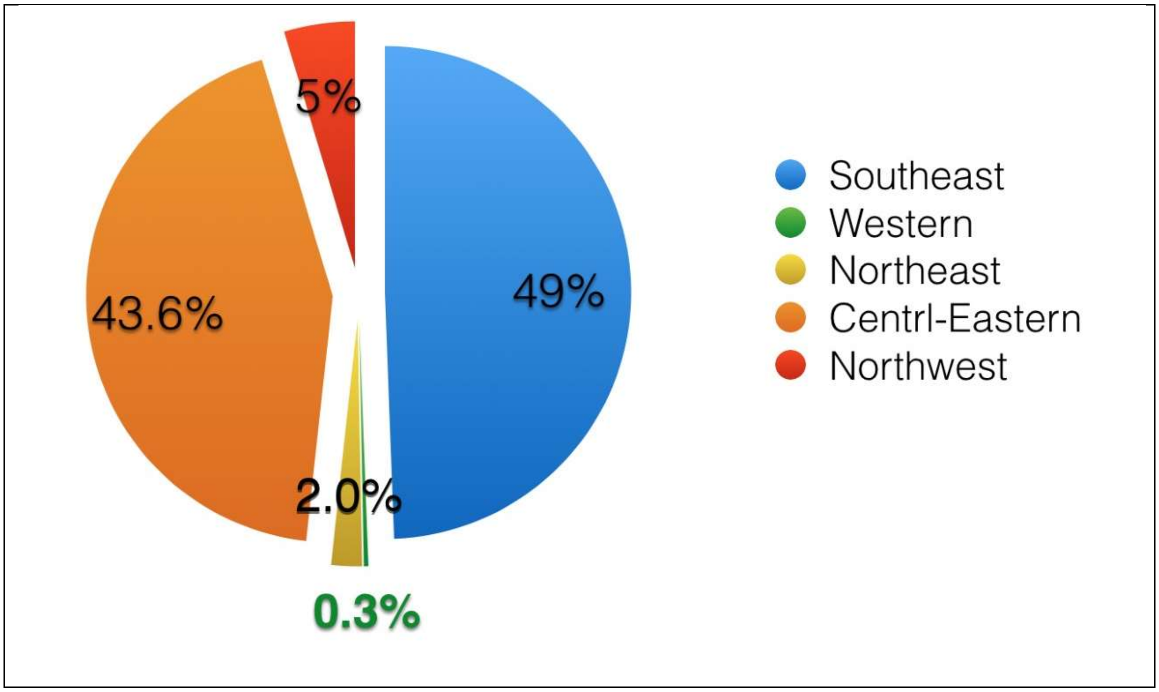

Figure 2. Estimated contribution to RFS (Vilsack, 2010).

In 2010, the southern United States generated a supply of 65 million tons for biomass feedstock (Sooduck, 2010). Potential feedstocks feasible for supplying biofuel production facilities in the Southeastern U.S. consist of soybean oil, energy cane, biomass sorghum, perennial grasses, and woody biomass. USDA assumes, according to the EISA, that biomass is grown on well-defined

agricultural cropland, meaning cropland where crops are produced, which does not include woody biomass.

Biomass utilization has become increasingly important for the timber industry. Biomass, in general, is considered as the total of organic matter in trees, crops, and living plant material. Woody biomass however, refers to the sum of materials collectable from a tree, including tops, limbs, needles/leaves, and woody fragments (OFRI, 2006). Timberland based feedstock, including wood residues, are feasible resources for biofuel production (Vilsack, 2010). Southern yellow *(Pinus taeda)* pine is a softwood species native to the Southern U.S. and is a resource for a variety of products. Due to its fast growth rate, lignin yield, and availability, southern yellow pine is an attractive biomass source (Owsley, 2011). Due to the emerging market and the rising demand of renewable fuels, the biomass industry has to focus on its operational effectiveness and increased efficiency to lower costs and maintain relevancy (Eisentraut, 2010). Current crude oil price development may suggest a decrease in investment on renewables (Figure 3). However, investments globally have risen by 17 percent, reaching $270 billion in 2014 (Nyquist, 2015). Dependence on imported energy, can also impact economy's stability significantly (Aguiar-Conraria *et al.*, 2006). In 2012, 40% of the U.S. petroleum demand were covered by net imports (EIA, 2013), see Table 1. In 2015, the United States imported about 9.4 million barrels per day (MMb/d). The

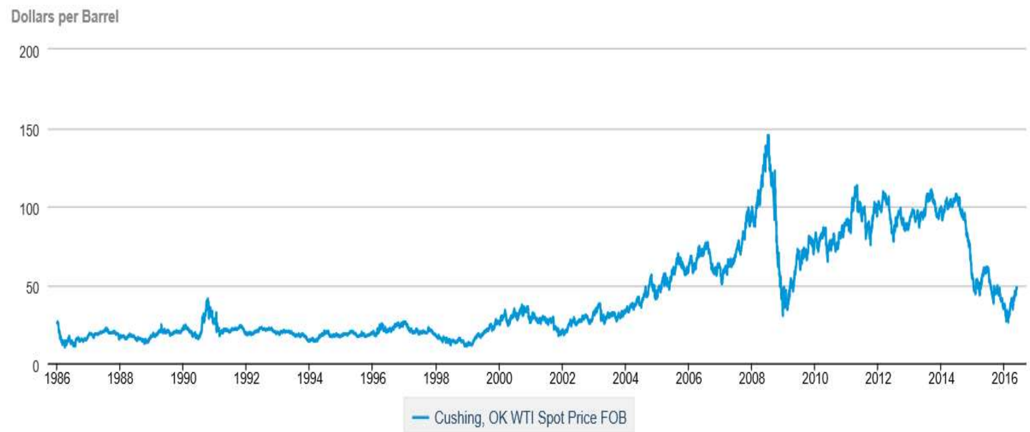

Figure 3. Cushing, Oklahoma (OK) West Texas intermediate (WTI) spot price FOB (Administration, 2016).

Table 1. Top Sources and amounts of U.S. Petroleum imports (EIA, 2016).

Top sources and amounts of U.S. petroleum imports, exports, and net imports, 2015 (million barrels per day)			
Import sources	**Gross imports**	**Exports**	**Net imports**
Total, all countries	9.40	4.75	4.65
OPEC countries	2.90 (31%)	0.	2.65
Persian Gulf counties (non-OPEC)	1.51 (16%)	0.01	1.50
Top five countries			
Canada	3.75 (40%)	0.95	2.81
Saudi Arabia	1.06 (11%)	0.00	1.06
Venezuela	0.83 (9%)	0.08	0.75
Mexico	0.76 (8%)	0.08	0.07
Colombia	0.39 (4%)	0.17	0.22

top five net importing countries were Canada, Saudi Arabia, Venezuela, Mexico, and Colombia (EIA, 2016).Due to the high percentage and therefore, dependence on foreign crude oil supply, concerns about geopolitical, national security, and economic consequences have arisen. Also, given the potential energy risks mentioned above, the U.S. congress advocated "energy independence" for United States, which resulted in the Energy Independence and Security Act (RAND, 2009).

Rationale for this Thesis

A key problem for biofuels is the large variance associated with feedstock quality and the ability of the manufacturing process to account for this variability, and the resulting influence this variability has on the variability of the quality of biofuel outputs. This 'large variance' problem directly influences the higher than necessary cost of final biofuel product, and inhibits biofuels to be price competitive in the market place. This thesis focuses on modeling the biomass supply chain of the 'bioenergy depot' (referred to in this thesis as the 'bio-depot') by estimating system and components variance which directly impact costs. The bio-depot is a concept focused on a centralized processing system, that receives woody biomass (*e.g.,* loblolly pine residuals) and Switchgrass, through separate supply lines. The biomass sources are then blended and converted into feedstocks with more uniformity in particle size geometry, moisture content, and ash content which conform better to the specifications of the biorefineries.

The thesis of this research is that by quantifying the system variance of the bio-depot and the variance of its components will help identify those components that have the greatest impact on cost in the bio-depot. Variance has a direct influence on cost of manufactured product (Taguchi *et al.*, 2004). The logistics component of the biomass supply chain and associated bio-depot contains multiple-stages where variation accumulates and increases the costs of the system. Statistical Process Control (SPC) and industrial statistics methods will be used to quantify variation; the Taguchi Loss Function will estimate the cost of the quantified variance (Taguchi *et al.*, 2004) (Deming, 2000).

Objectives

The objectives of the thesis are:

1) Defining the upstream of the supply chain for loblolly pine,
2) Develop a logistics map from harvest site to plant-gate,
3) Develop a reliability block diagram with components of variance for the bio-depot within the plant gate,
4) Define the key metrics in the supply network, based on 1a,
5) Quantify the variation for the key metrics;
6) Create an Excel simulation spreadsheet for 1a and 1b, and 1c,
7) Simulate the process by assuming a Gaussian or normal distribution for variation;
8) Apply the Taguchi Loss Function to estimate cost of variation for 1a, 1b and 1c;

9) Conduct simulations to estimate costs and illustrate methods for reducing cost.

CHAPTER II. LITERATURE REVIEW

Background Analysis

Historical Background of Supply Chain Evolution

In the early 20th century, Henry Ford redesigned the supply chain of his company. Manufacturers and producers have dealt with logistics and supply chains ever since. A healthy and sustainable supply chain became a symbol for a competitive and beneficial enterprise (Rushton *et al.*, 2014, p. 7). Ford saw the need for a variety of products, but he also recognized the complexity of a broad selection shown as an accumulation of waste in production resulting in unwanted costs (Goldsby *et al.*, 2005). General Motors anticipated the customers' needs and offered its products in a variety of specification options (Shah, 2009). A major issue of logistic systems in the 1950s was an uneven workload distribution and lack of information within the chain (Rushton *et al.*, 2014). Between 1960 and 1970, Toyota initiated the Toyota Supply Chain. The Toyota Motor Company started to assemble and manufacture key components in their own production sites; other components were provided by third-party suppliers. Toyota built a supply network with partners with in short distance to the main plant. This strategy reduced the time needed to change a setup from hours down to several minutes (Shah, 2009). With the rise of technology and the fast exchange between enterprises, supply chains have become more complex and accurate. For example, the computer manufacturer Dell did not focus on long-term relations to

suppliers but instead made short-term contracts only to highly flexible suppliers. Suppliers delivered on a just-in-time basis to ensure that Dell's CPUs were assembled according to the demand of the consumer. The Dell monitors, however, went directly from the supplier to the customer in order to reduce storage cost (Figure 4) (Taylor, 2004).

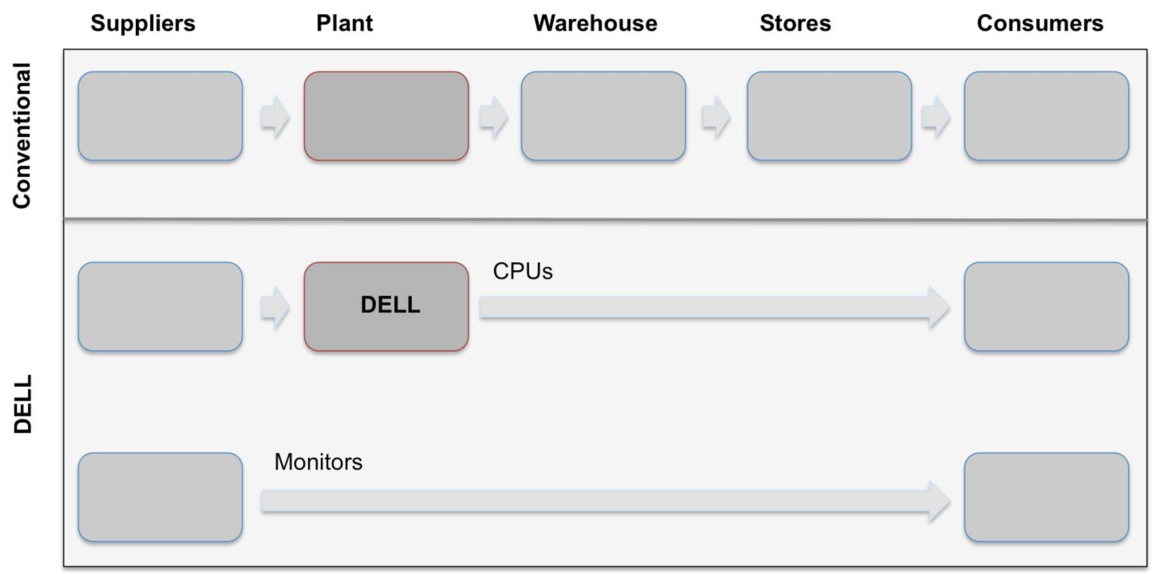

Figure 4. Dell's Supply chain strategy (Shah, 2009, p. 7).

Supply Chain Today

In today's economy, companies are dealing with the "network competition age." Sophisticated marketing plans and well-resourced showrooms are not a guarantee for success anymore, and the paradigm has shifted to supply chain competition. Markets are characterized by rapid changes and fluctuation in demand (Erturgut, 2012). Modern supply chain management (SCM) is operating

under increased variability and constant reorganization due to changes in the market. Information Technology practices enable direct and fast communication between nodes integrating the supply network into the value system (Marinagi *et al.*, 2014). SCM practices have a direct influence on both organizational performance and competitive advantage (Figure 5) (Li, 2004).

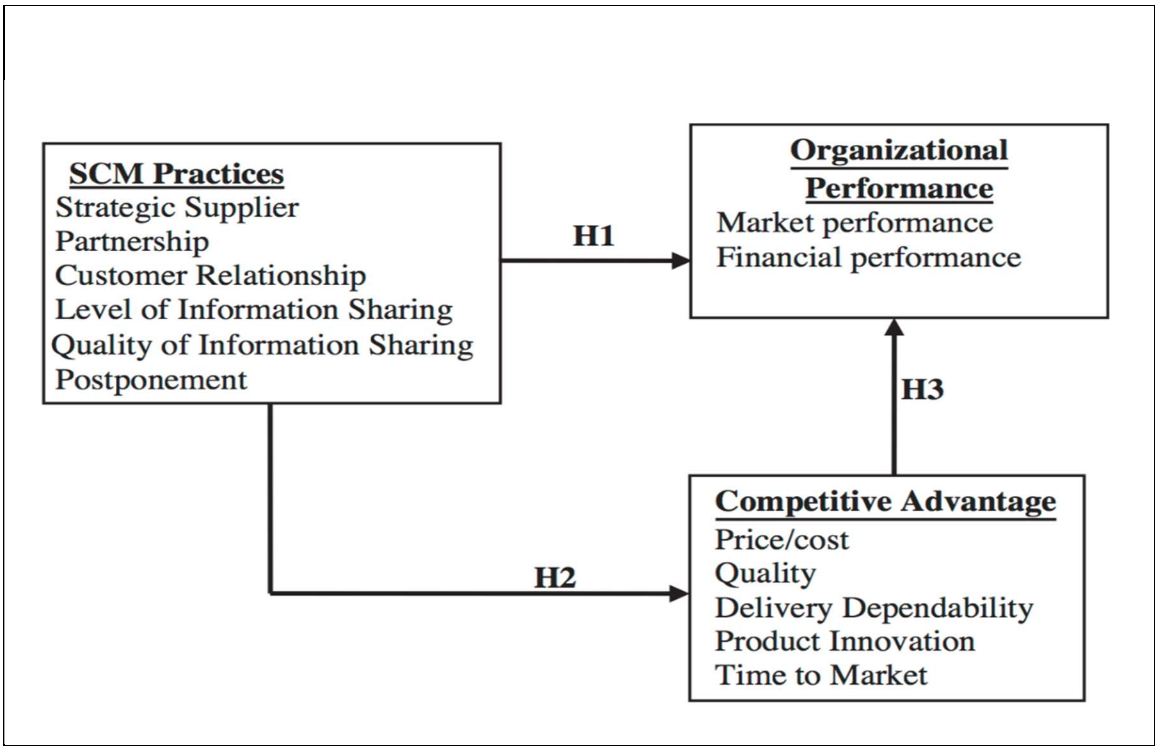

Figure 5. Influence of SCM on organizational performance and competitive advantage (Li, 2004).

SCM operations have to improve the throughput in combination with low storage and work in process. A significant driver of a firm's success is linkage between Just in Time (JIT), Total Quality Management (TGM), and SCM practices.

Effective integration of these practices into operations management improves performance and therefore, creates value and reduces overall costs (Kannan *et al.*, 2005). Supply chains can be split into two categories, independent from enterprise size, namely upstream and downstream (Figure 6).

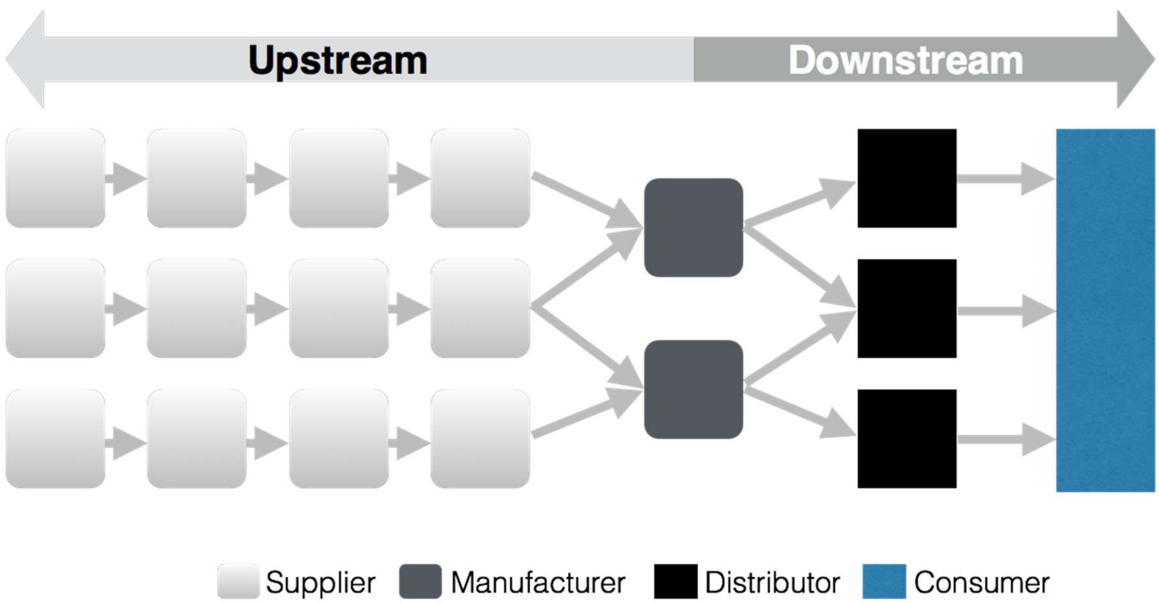

Figure 6. Segments of a supply chain.

Upstream refers to partners that provide the manufacturer with goods and services needed to satisfy demands. The supply side of the supply chain also includes other flows such as return product movements, payments for purchases and can be described as the opposite of a downstream. Downstream defines the flow of goods and services from the manufacturer to the consumer. This section is also known as the demand side of the supply chain, were usually third party companies support a manufacturer with the distribution goods (Visions, 2010).

Biomass

Biomass Supply Chain/Logistics

The literature reviewed for this chapter focuses on commonly used techniques to monitor and improve supply chains. This includes the identification of supply network issues and the application of models.

Biomass supply is built on a multicomponent supply network that faces availability challenges. This network can be described as a construct of five stages: feedstock production, feedstock logistics, biomass processing, biomass product distribution, and biomass end-product (Parish *et al.*, 2012). The feedstock logistics stage includes all needed procedures to transport feedstock from harvest site to the production facility's gate (Chung, 2010). A layout that emphasizes activities needed for transporting feedstock from the production point to a power station is described in six steps: Harvesting/collection, In-Field/Forest Handling, Storage, Loading/Unloading, Transportation, and Processing (Rentizelas *et al.*, 2009). Figure 7 illustrates the process of a uniform format feedstock supply system. 'Depots' (*i.e.,* intermediary processing station) are located strategically close to harvesting sites of the feedstocks. These depots include a preprocessing stage to ensure higher throughput quantities in transportation (Hettenhaus *et al.*, 2004). Preprocessing feedstocks have a major influence on transportation performance. The U.S. Department of Transportation declares the maximum weight limit for a truck to be 80,000 lbs. (approximately 40 tons), even though this varies by state

regulations. Transportation parameters have to be taken into consideration when it comes to the preprocessing procedure. There are a number of established equipment options for harvest and on-site preprocessing.

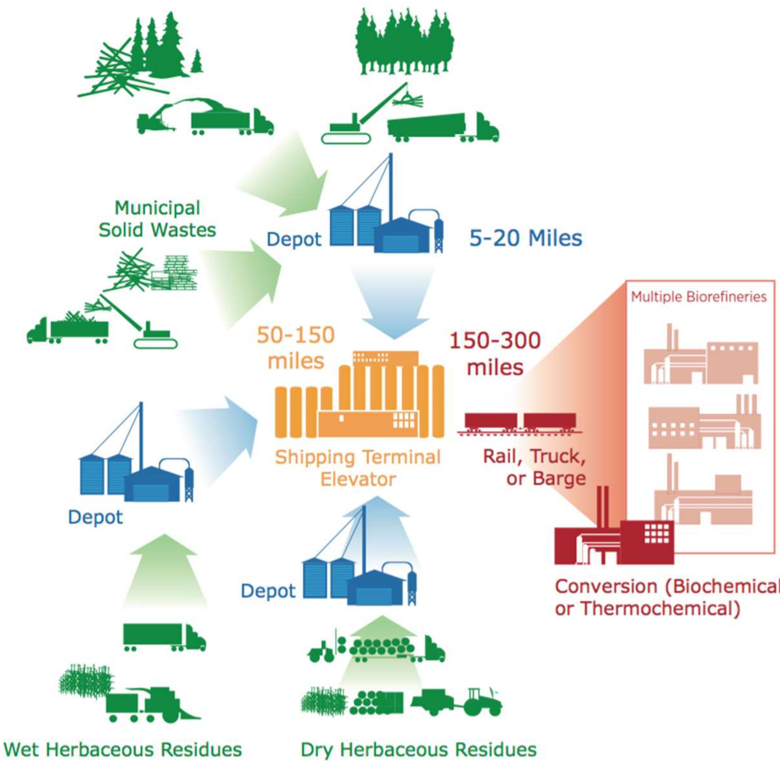

Figure 7. Feedstock supply system (Hettenhaus *et al.*, 2004)

The level of preprocessing has a direct impact on entire efficiency of the supply chain (Figure 8.). Density is a limiting factor of the supply chain for bio-based feedstocks like Switchgrass (*Panicum virgatum L.*). For example, the density of chopped Switchgrass is around 70 kg/m^3 while pelleted Switchgrass has a density of 700 kg/m^3 (Sooduck, 2010). Switchgrass is harvested seasonally.

Therefore, long term storage of feedstock has to be accounted for to ensure a stable annual supply. A challenge of the storage process is trying to minimize loss of feedstock due to decay. (Uslu *et al.*, 2008). Keefe *et al.* (2014) created a flow map for woody biomass, including different logging, preprocessing, and logistics-options.

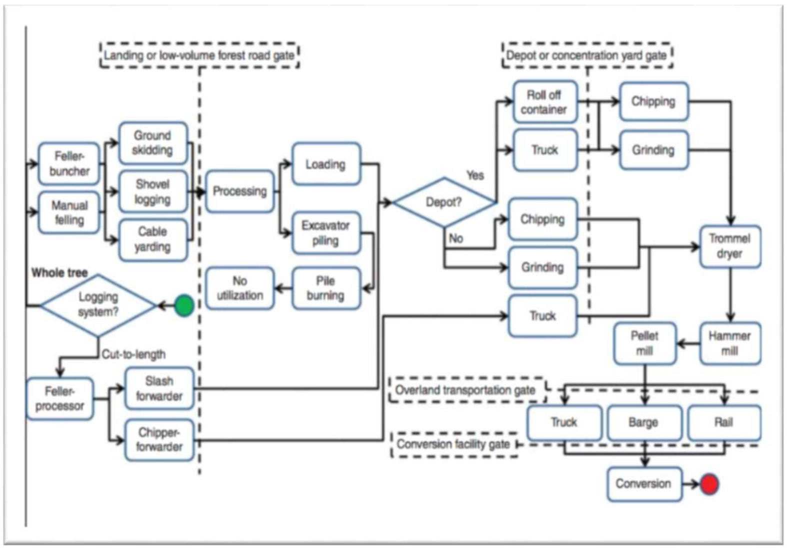

Figure 8. Example of possible primary woody biomass supply chain (Keefe *et al.*, 2014).

All these steps are potential causes for variation (Keefe *et al.*, 2014). A bio-depot concept attempts to reduce variability of key feedstock characteristics, *e.g.,* particle size, ash content and moisture content. The depot must be able to assess and quantify the variability of feedstock characteristics in order to meet the specifications and reduce the variability of the output feedstocks. Biomass feedstocks are typically blended to meet the target (Mafakheri *et al.*, 2014).

However, blending does not reduce the sum of the component variances, *i.e.,* variance is additive as defined mathematically for any series or parallel system.

The variance for a two component parallel system with independent components is defined as:

$$Var\ (A + B) = Var\ (A) + Var\ (B). \qquad [1]$$

The variance for a two component series system with dependent components is defined as:

$$Var\ (A + B) = Var\ (A) + Var\ (B) \pm 2COV(A, B), \qquad [2]$$

assuming equal variance for each component,

or,

$$Var(aX + bY) = a^2 VarX + b^2 VarY \pm 2abCov(X, Y) \qquad [3]$$

assuming unequal variance for each component. The Bio-depot is similar to a series or dependent system.

Feedstocks of the Bio-Depot Addressed in this Thesis

Loblolly Pine (Pinus taeda)

Loblolly pine *(Pinus taeda)* is native to the Atlantic and Gulf coastal plains of the United States (Figure 9). The soil requirements of this coniferous tree shares similarities with Switchgrass; both plants grow on sandy and relatively infertile ground. This is one reason why loblolly pine is preferable for reforestation and

erosion control (Owsley, 2011). The elevation requirement ranges from approximately sea level up to 1,970 feet (600m). Most of the loblolly pine forests are found at elevations below 660 feet (200m). The high quality timber of loblolly pine is well suited for sawlogs, poles, pulp, and plywood. At twenty years of age, the yield/ha is approximately 874 ft^3 (61 m^3) (Boyer, 1993). The range of loblolly pine is from southern New Jersey to eastern Texas, down to central and south Florida (Figure 9).

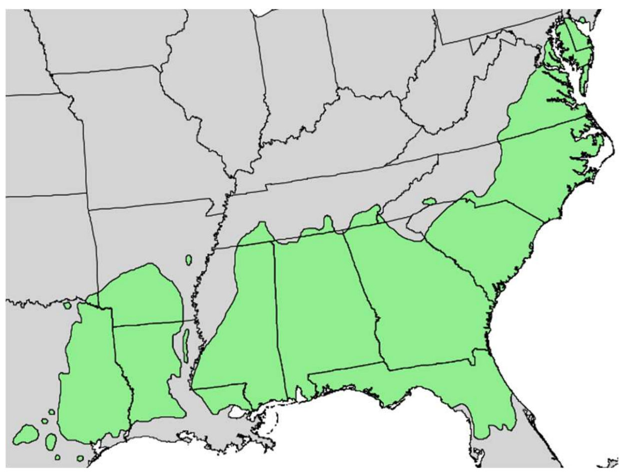

Figure 9. Native spread of Loblolly Pine (Little, 1966).

Due to its adaptability, loblolly pine was introduced to other continents, such as Africa and Australia (J. B. Baker *et al.*, 1990). Figure 10 is an illustration of stages of biomass upstream process, starting with the harvest site. The stages all contribute to the feedstock's total variance of feedstock quality attributes. Three feedstock characteristics are included in this thesis for simulating variance and

estimating costs, *e.g.,* particle size geometry of processed wood and Switchgrass, moisture content, and ash content.

Switchgrass (Panicum virigatum L.)

In 1978, the Department of Energy (DOE) mandated that Oak Ridge National Laboratory (ORNL) investigate the potential of fast growing trees as well as crop residues for renewable energy. ORNL assessed more than 30 herbaceous crops; Switchgrass was determined as the most beneficial high yielding perennial grass species. In 1991, Switchgrass (*Panicum virigatum L.*) was declared as a model energy crop (Mohammed *et al.*, 2015). Switchgrass's compatibility with common farming procedures led to the decision to use Switchgrass as resource for bioenergy (Sanderson *et al.*, 1996). Switchgrass is a perennial bunch grass native to southeastern and central United States shown by the distribution map (Figure 11).

The grass is climatically adapted throughout most of the United States. The distribution map emphasizes the minor soil requirements of Switchgrass.

The best growing regions are those with a dry to poorly drained soil, as well as sandy or clay soils. Switchgrass doesn't perform as well on dense soils, also known as heavy soils (Parrish *et al.*, 2005). The grass grows from one to three meters in height, without extensive environmental or genetic influence, and its roots can penetrate the soil up to a depth of 3 meters (Luo *et al.*, 2014). Switchgrass requires two to three years of establishment to be considered fully

applicable for commercial use. This perennial grass is then harvestable for up to 15 years before replanting is necessary (Lu *et al.*, 2015).

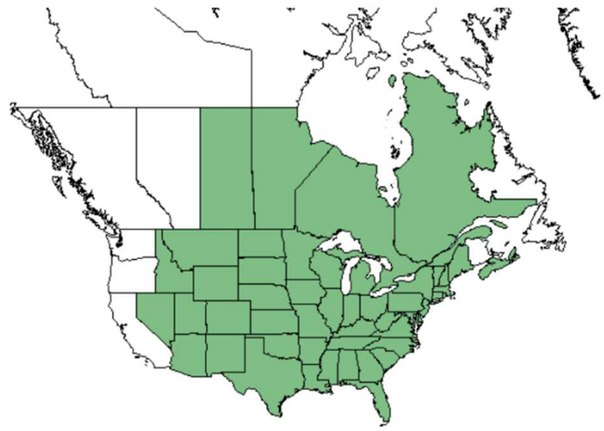

Figure 10. Native spread of switchgrass (Database, 2009).

The limited time frame of Switchgrass harvesting season makes a continuous supply throughout the year difficult. Therefore, several suppliers/supply-lines have to be used by the bio-depot for a continuous supply to the manufacturing facility. Suppliers deliver different varieties of Switchgrass which creates variations in the feedstock quality (*e.g.,* ash content, etc.). Blending of feedstocks is typically done to try to meet the required target requirement (*e.g.,* ash content), but this does not reduce total variability (recall equations [1] and [2] that variance is additive). The total variance of the blend must meet the specifications of a bio-refinery. Switchgrass biomass production includes several processing steps (Figure 12). There is a large body of literature regarding the modeling and optimization of supply chains for different feedstocks, products,

processes, system properties, and from various modeling viewpoints (Yue *et al.*, 2014). The increased interest in cellulosic biofuel production, generated from forest residues, agricultural wastes, and energy crops (Naik *et al.*, 2010). Numerous studies have focused on the availability of cellulosic biofuel supply. Prior research stated that there is sufficient quantity of potential feedstocks to meet the requirements of EISA (Perlack *et al.*, 2005).

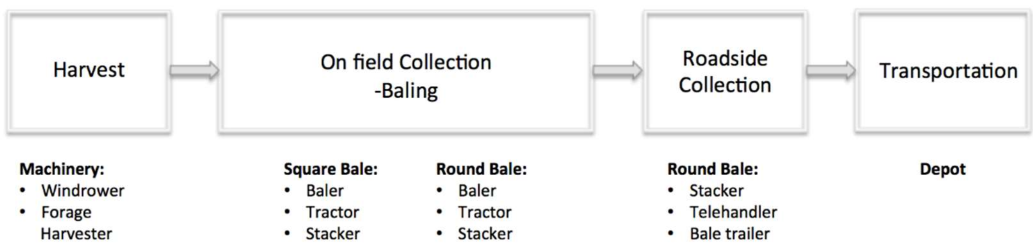

Figure 11. Field handling and equipment specification of Switchgrass biomass.

Biomass has the advantages to be a versatile energy sources, generating not only electricity, but heat. Energy from biomass can be produced on demand, which makes it a promising fuel of the future (Rentizelas *et al.*, 2009). The demand and consumption of bio based energy will rise significantly, which confronts the bio based energy sector with one of its major concerns, a secured and effective supply chain (De Meyer *et al.*, 2015). A large fraction of cost of biomass energy production comes from transportation and handling (Hettenhaus *et al.*, 2004).

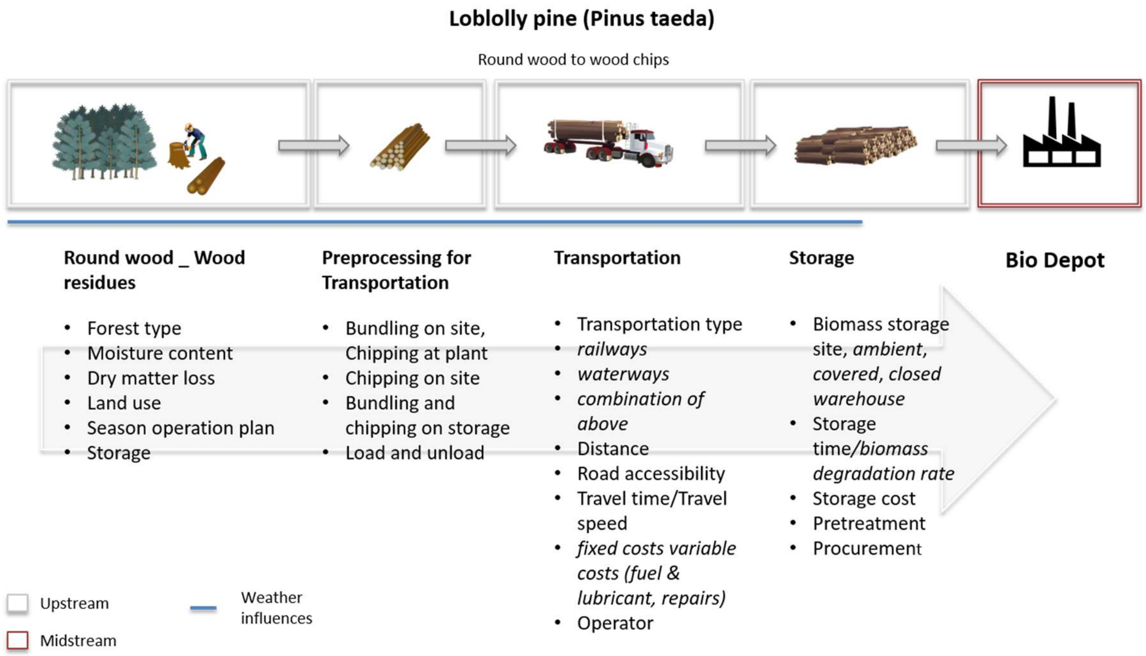

Figure 12. Loblolly Pine (*Pinus Taeda*) processing steps for the bio-depot concept.

There is an increased interest in increasing global production of biomass and bio based energy as a substitute for fossil fuels. This substitution contributes to the mitigation of greenhouse gas emissions. Despite the benefits of biomass usage, technical and economic challenges prevent the paradigm shift for bioenergy to develop at a fast pace (Cambero *et al.*, 2014). Key issues with a competitive bioenergy price are related to the difficult supply chain management. An optimized and efficient supply chain management is required to adjust to detailed conditions of the corresponding feedstock, production system, logistics, and handling (Gold *et al.*, 2011). The purpose of efficient biomass handling and transportation is to

keep the cost factor competitive compared to fossil fuels. Sufficient supply of feedstock relies on consistent growing cycles, negatively influenced by unpredictable natural causes (Awudu *et al.*, 2012). Biomass allocation and supply equilibrium (BASE) addresses major questions of cost factors concerning biomass use and biomass logistics. This analysis accounts for the costs and losses from the harvest site to the end user (Ruth *et al.*, 2013). A review of the literature indicted that no citations exist as related to the objectives of this thesis.

Statistical Process Control

Walter Shewhart (1891-1967)

With this statistical tool, expanded by W. Walter Shewhart, an American physicist, engineer, and statistician invented control charts to monitor a process performance (Best *et al.*, 2006). Control charts are an essential feature of SPC. Edwards Deming (Austenfeld, 2001), it is possible to improve processes via reduction of variation, which is necessary for an organization's survival (Wheeler *et al.*, 2010).

In 1924, when Shewhart invented the control chart, statistical methods were not widely used in manufacturing (Wilcox, 2003). Shewhart wanted to emphasize that variation is found in any process, product, or organization. Where manufacturing was focusing on meeting the specification, Shewhart tried to improve process consistency as long as the products met "spec," results were good enough for manufacturing. Specification limits are only accurate if they meet customers' needs. To meet demand, a process has to continuously adapt according to the

change in demand (Wilcox, 2003). While working for Bell Telephone Laboratories, Shewhart refined his control charts and was able to apply these in manufacturing. Instead of a 100% inspection policy, Shewhart introduced inspections based on sampling. Statistical quality control was widely applied in Western Electric facilities by the mid 1930's (Montgomery, 2009). In 1939, Shewhart published his book "Statistical Method from the Viewpoint of Quality Control," (Best *et al.*, 2006) which was a milestone for modern production systems and therefore, SPC, TQM, Six Sigma and Lean Manufacturing.

W. Edwards Deming (1900-1993)

While pursuing his PhD Deming spent the summer working for Western Electric, where Deming met Shewhart. Deming obtained his doctorate in mathematical physics at Yale in 1928 and became (Best *et al.*, 2005) a mathematical physicist for the Department of Agriculture. Deming supported American troops during World War II as a statistical advisor concerning statistical quality control and sampling methods. His input had tremendous effect on production performance with a heavy reduction in rework (Neave, 1987). In 1950, Deming lectured a vast number of engineers and managers in SPC. Despite the positive impact his methods had on the production of goods for WWII, American companies didn't realize the potential of Deming's ideas (Best *et al.*, 2005). Deming's basic teachings:

- The chain reaction: quality, productivity, lower costs, capture the market,

Table 2. Commonly used methods for improving supply chains.

Quantative Modeling Method	Citation
Supply Chain Design	(Elia et al., 2012),
Ant Colony heuristic procedure	(Zamora-Cristales et al., 2015)
Area Restriction Model	(Gunnarsson et al. 2004)
Game Theory and Special Market Equilibrium	(Dutta, 1999), (Myerson, 1997), (Bai et al. 2012)
Goal Programming Method	(Yue et al., 2014)
Heuristics Algorithms and Metaheuristics	(Mula et al., 2010), (Chern et al., 2007),(Power, 2005), (Thomas et al., 1989)
Superstructure Optimization	(Lababidi, 2004; Roghanian et al., 2007)
Robust Optimization	(Sahinidis, 2004)
Unit Restriction model (URM)	(Mafakheri et al., 2014)
Simulation models	(Ferreira et al., 2011)
Greet Model	(Lu et al., 2015)

- Productivity viewed as a system,
- The Fourteen Points for transformation of management,
- The Seven Deadly Diseases,
- The Plan, Do, Study, Act (PDSA) Cycle,
- The Red Bead experiment,
- The Funnel experiment,
- The system of profound knowledge (Austenfeld, 2001).

His lectures to the Japanese Union of Scientists and Engineers (JUSE) however, influenced many Japanese companies and their approach on quality control. Due to his impact on Japanese firms and the resulting post war recovery, Deming was recognized with the Deming Prize founded by JUSE in 1951. This prize is the highest honor a Japanese company can receive for quality control.

Ichiro Ishikawa, a chairman of JUSE, gave Deming the chance to talk to 21 of Japan’s top managers. At the time, Deming evolved his idea of the “Shewhart Cycle” (Figure 13) (i.e., the Plan-Do-Check-Act or PDCA cycle) and was able to gain the interest of Japanese business elites.

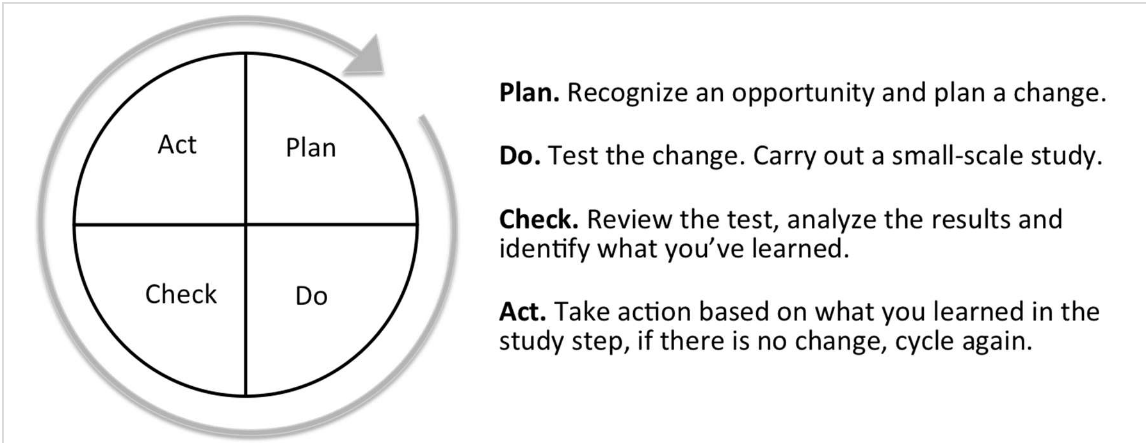

Figure 13. Shewhart Cycle/ Deming Cycle (Deming, 2000).

Back then, manufacturers were focused on designing a product, production, and sales. The big mistake found by Deming was that there was no evidence that the consumer had any need for the product. Deming introduced the "Shewhart Cycle" to the managers: (Austenfeld, 2001):

1. Design the product,
2. Make it, test it in production/laboratory,
3. Put it on the market,
4. Test it in service, through market research, research the costumer,
5. Re-design the product according to costumers' needs,
6. Loop those 5 steps (Austenfeld, 2001; Wheeler *et al.*, 2010).

This process was condensed as the PDCA, Plan Do Act Check.

In 1986, Deming's combined practices were published in the book "Out of the Crisis" (Deming, 2000). This work represents all quality improvement tools that he worked on throughout his life. In this book, Deming presented fourteen key principles, principles that management of any kind of company could use to achieve continuous improvement.

Deming's 14 points were:

1) **"Create constancy of purpose towards improvement."** Replace short-term reaction with long-term planning.

2) **"Adopt the new philosophy."** The implication is that management should actually adopt his philosophy, rather than merely expect the workforce to do so.

3) **"Cease dependence on inspection."** If variation is reduced, there is no need to inspect manufactured items for defects, because there won't be any.

4) "Move towards a single supplier for any one item." *Multiple suppliers mean variation.*

5) **"Improve constantly and forever."** Constantly strive to reduce variation.

6) **"Institute training on the job."** If people are inadequately trained, they will not all work the same way, and this will introduce variation.

7) **"Institute leadership."** Deming makes a distinction between leadership and mere supervision. The latter is quota- and target-based.

8) **"Drive out fear."** Deming sees management by fear as counter- productive in the long term, because it prevents workers from acting in the organization's best interests.

9) **"Break down barriers between departments."** Another idea central to TQM is the concept of the 'internal customer', that each department serves not the management, but the other departments that use its outputs (Young, 2015).

10) **"Eliminate slogans**." Another central TQM idea is that it's not people who make most mistakes - it's the process they are working within. Harassing the workforce without improving the processes they use is counter-productive. Deming's Bead Box Experiment.

11) **"Eliminate management by objectives**." Deming saw production targets as encouraging the delivery of poor-quality goods.

12) **"Remove barriers to pride of workmanship."** Many of the other problems outlined reduce worker satisfaction.

13) "Institute education and self-improvement."

14) "The transformation is everyone's job."

Joseph M. Juran (1904-2008)

Juran, an American engineer and consultant, is considered to be the founding father of Total Quality Management (TQM). Juran was aware of the importance of human resources and related actions towards the goal of high quality products. Juran focused on empowered organizations, where employees align their goals and responsibilities with the firm's duty to satisfy the customer needs. The concept of an empowered organization is described as: Empowerment = alignment x authority x capability x commitment (Joseph M. Juran *et al.*, 1998). If TQM is applied correctly, it should result in lower costs, higher revenues, empowered employees, and delighted customers. The importance of these results is captured in Figure 14.

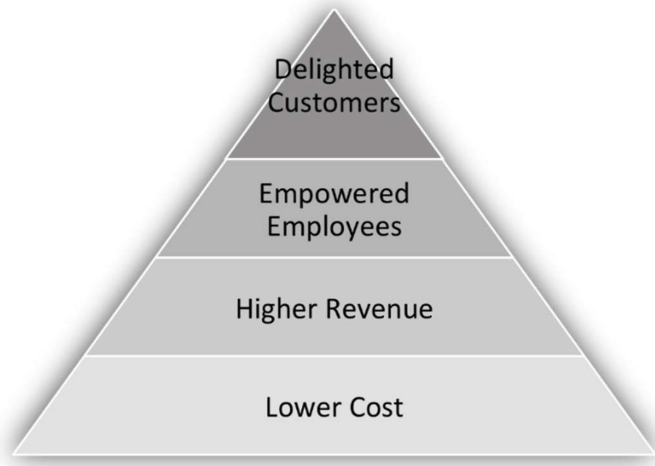

Figure 14. Joseph M. Juran - Results of TQM (Joseph M. Juran *et al.*, 1998).

Joseph M. Juran developed the “Quality Trilogy” also known as the “Juran Trilogy”. This trilogy deals with the concept that quality oriented managing consists of three steps.

Quality Planning: Creating a technique/process that has the capability of meeting specifications under certain conditions that are established by operations.

1. Identify the customers, both external and internal.
2. Determine customer needs.
3. Develop product features that respond to customer needs. (Products include both goods and services).
4. Establish quality goals that meet the needs of customers and suppliers alike, and do so at a minimum combined cost.
5. Develop a process that can produce the needed product features.
6. Prove process capability—prove that the process can meet the quality goals under operating conditions.

Quality Control: Pursuing optimal effectiveness of any kind of process. Flaws/waste that are implemented in the process during the planning phase have to be addressed and eliminated. Quality control prevents waste/quality from getting under specifications/control limits.

- Choose control subjects — what to control.
- Choose units of measurement.
- Establish measurement.
- Establish standards of performance.
- Measure actual performance.
- Interpret the difference (actual versus standard).
- Take action on the difference.

Quality Improvement: A process step implemented by management in, addition to quality control, to ensure continuous improvement.

- Prove the need for improvement.
- Identify specific projects for improvement.
- Organize to guide the projects.
- Organize for diagnosis—for discovery of causes.
- Diagnose to find the causes.
- Provide remedies.
- Prove that the remedies are effective under operating conditions.
- Provide for control to hold the gains (J.M. Juran, 1986).

Joseph M. Juran inspired Apple founder and former CEO Steve Jobs (1955-2011) to question the reason for a process's success. Jobs described Juran's advice to him: "*Look at everything as a repetitive process and instrument that process to find the reason why it is working. So that one is able to take it apart and reassemble it with improved effectiveness*" (Jobs, 1990).

Lean Principles

Lean principles, an invention by the Toyota Motor Corporation, is also known as Toyota Production System. The oldest component of TPS, Jidoka, was invented by Sakichi Toyoda in 1902. Jidoka focuses on autonomation and therefore, more productivity within the system combined with less time, space, and effort while meeting customers' needs (Dennis, 2002). The Japanese terminology where Lean originated is three specific kinds of waste: Muda, Mura, and Muri. Muda identifies waste of time and material, Mura addresses variation, and Muri emphasizes overburdening of workers or systems (Young, 2015). The reduction of inventories, waste, and improvement of the overall system performance are the main ideas behind this instrument. Toyota addressed seven kinds of waste in their production (Table 3). Due to the definition of the problem's source, it is easier to improve the process. One essence of lean is to specify the value desired by the costumer (Young, 2015). Questioning each and every step within the production is beneficial for a continuous workflow. Value-added tasks should be maximized,

where other steps of non-value or waste should be eliminated. The seven waste factors are (Dennis, 2002):

Table 3. Seven types of waste (Young, 2015), (García-Alcaraz, 2014).

7 Types of Waste	Causes of Waste	Consequence
1. Correction	Poor internal quality	• Extra handling • Additional labor • Risk of additional defects, delivering inferior products
2. Overproduction	Machine breakdowns, Wrong interpretation of efficiency, Variation in loads	• Necessity for additional parts, storage, materials • Increase in conveyance • Growth of stock
3. Waiting	Breakdowns, Changeovers, Delays, Poor Layout	• Unnecessary cost • Imbalanced workflow
4. Conveyance	Inefficient facility design	• Materials and people move more than necessary

Table 3. Continued Seven types of waste (Young, 2015), (García-Alcaraz, 2014).

7 Types of Waste	Causes of Waste	Consequence
5. Processing	Wrong use of machinery, Insufficient machinery	• Production of products that are over or under customer specification
6. Inventory	Unequal capabilities within process	• Work in process (WIP) • Unbalanced work distribution • Cost/space • Additional handling/labor
7. Motion	Unnecessary movement	• Time and energy

CHAPTER III. MATERIALS AND METHODS

Bio-Depot Concept

A challenge of supplying southern pine and Switchgrass is the high cost of transportation and handling (Lu *et al*., 2015). The research in this thesis will demonstrate the potential of a new type of biomass supply system (*i.e.,* “The Bio-Depot”). The biomass supply system includes a centralized processing system within the supply chain which blends feedstocks in attempt to meet the target and specifications of biorefineries. The processing facility, also called “bio-depot’ (or ‘merchandising depot’), will convert stems of woody biomass (includes limbs and leafy materials) into the feedstocks for biofuels. This step is envisioned to reduce handling costs for bioenergy production (Figure 15). The bio-depot will include several processing modules. Establishing this bio-depot within upstream supply chains of biomass is envisioned to increase throughput capacity while reducing variation and lowering costs. This thesis will simulate variation within the bio-depot. This thesis uses conceptual modeling which is an abstract view of the process. The process is described with a simplified model. Conceptual modeling is usually based on assumptions taken from real systems (Robinson, 2010), see Figure 16.

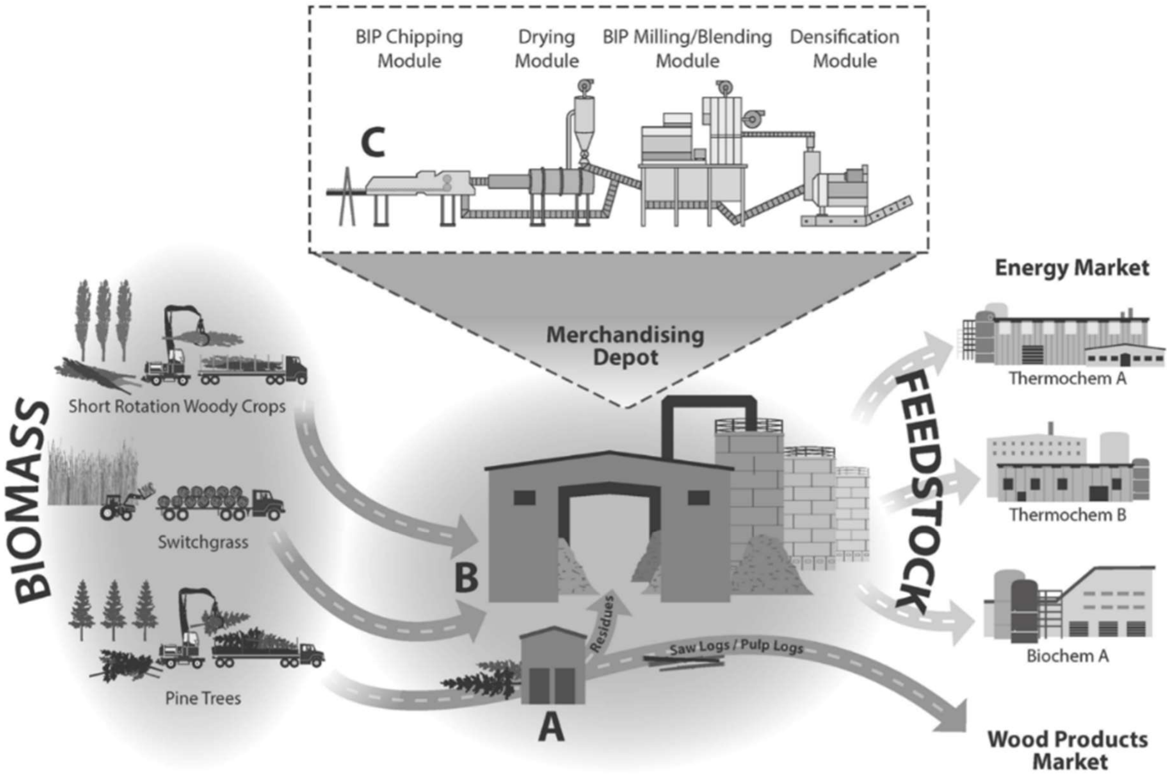

Figure 15. Merchandizing system for consistent feedstock.

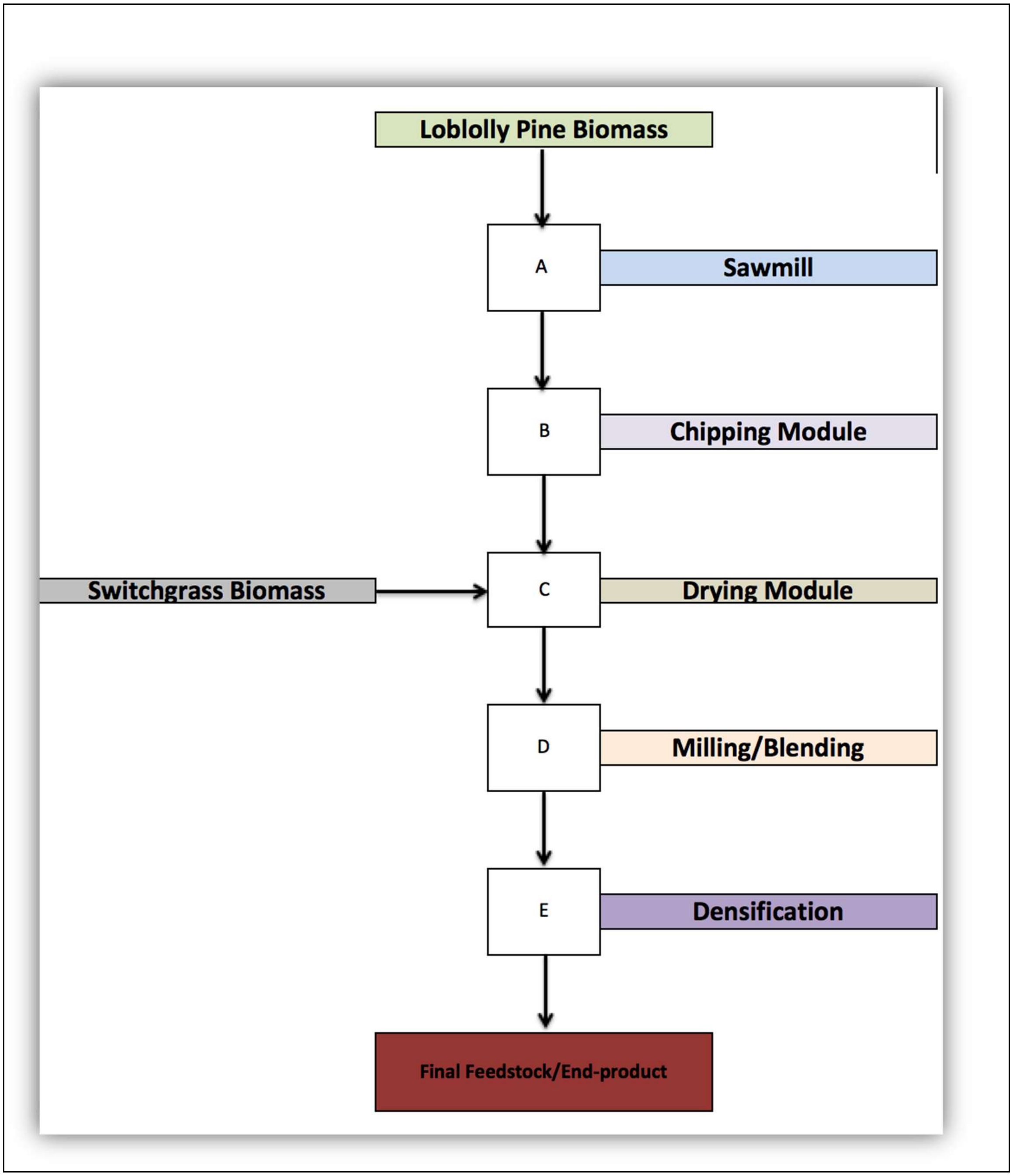

Figure 16. Conceptual model of bio-depot.

The different stages of the conceptual model are described below.

Component A - Sawlog or round wood supply

Full southern pine trees will be hauled to a sawmill for example; and will then be converted into high valuable wood products, as well as clean supply of woody residues. The sawmill will provide the merchandising depot with residues from the pine sawlogs (*e.g.,* limbs, treetops, and needles). It is believed that the ash content will be reduced relative to producing this residue material from in-woods harvesting operations. Ash content or ash contamination is key problem with biomass feedstocks. Sawlogs typically yield many products and residues after being processed, as displayed in Figure 17.

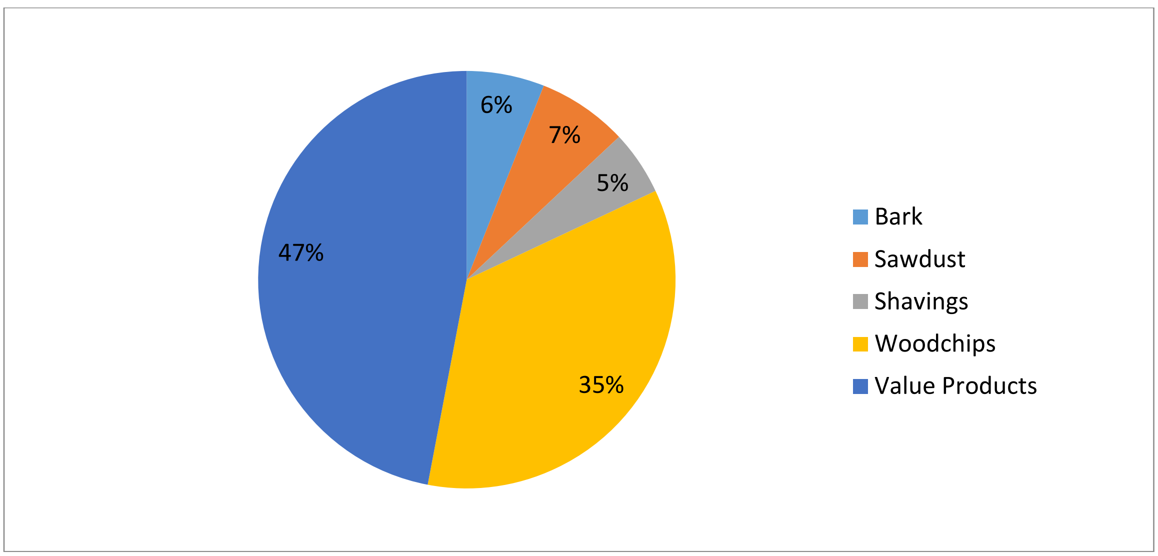

Figure 17. Softwood produce quantities from a sawmill (Dean Goble, 2013).

These quantities vary by diameter of the log (Dean Goble, 2013). The quantity of residue produced by timber processing plants differs from properties of timber, timber species, tool condition, maintenance intervals, etc. However, averages proportion of residues produced from different wood processing industries is presented in Table 2.

Table 4. Proportion of wood residues generated by wood processing manufacturers excluding bark (Murray, 1990).

	Sawmilling	Plywood Manufacturer	Particle Board Manufacturer	Integrated Operations
	%	%	%	%
Finished Product (Range)	45-55	40-50	85-90	65-70
Finished Product (Mean)	50	47	90	68
Residues	43	45	5	24
Losses	7	8	5	8
Total	100	100	100	100

Component B – Knife-ring Flaker

The bio-depot concept foresees to generate supply from preprocessed timber residues. Preprocessing is done by a sawmill. The Clean wood chips are produced from clean wood after debarking. Dirty chips are produced from entire trees, the chips include bark, needles, branch wood, and contaminations. Contaminations may consist of such things as soil and gravel (Mackes, 2010). According to the International Organization for Standardization (ISO), and

therefore EN ISO 17225 series (Standard for Solid Biofuels), fuel specifications and classes for wood chips are:

EN ISO 17225-1: General Requirements

EN ISO 17225-4: Graded Wood Chips

The EN ISO 17225 also included standards and requirements for wood pellets briquettes, and firewood (ISO, 2014). However, no comparable standards where found that apply for the United States.

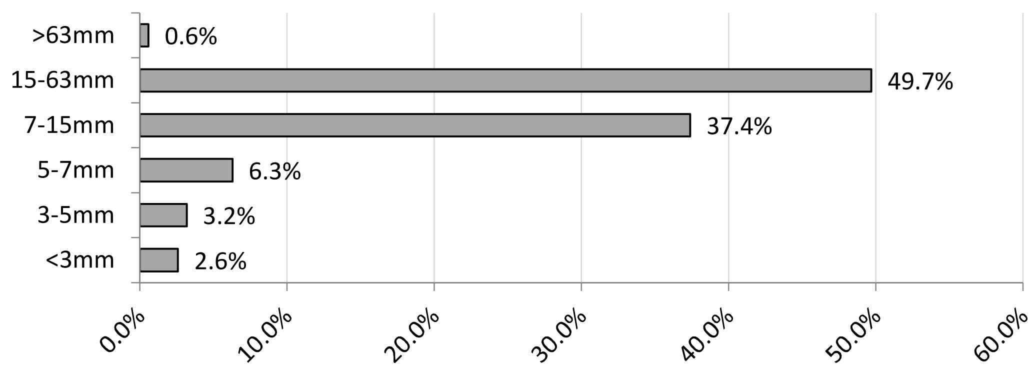

Figure 18. Loblolly pine chip size distribution after drum style shipping (S. Baker *et al.*, 2011).

The knife-ring of wood residues is required to produce uniform sized wood chips for the drying process (*i.e.,* Component C - Drying Module which is discussed later). The handling of stems and limbs is performed by a drum style chipper. Processing loblolly stems with a drum-style chipper results in a chip size distribution from three mm to 63mm (Figure 19) (S. Baker *et al.*, 2011). After the

intermediate step of knife-ring, previous studies prove that the moisture content of chips have an average 55% green-weight basis (Mackes, 2010).

The received wood chips are converted into smaller particles, by crushing the material using a knife-ring flaker. A knife-ring flakers (Figure 20) use the principle of converting cut woody material into strands, wafer or, flakes. The material is feed into a chamber that is encompassed by a blade ring, which rotates at high speed. Not only does the drum cut the material into smaller particles, furthermore, the material is moved slowly, which enables a continuous flaking process.

Figure 19 Knife-ring flaker (Hombak, 2013)

Component C - Drying Module

Available techniques for drying various types of biomass have a direct impact on dry matter loss and fuel quality (Jirjis, 1995). Rotary drum dryers are the most commonly used machinery to decrease the moisture content of wood flakes and particles. The dryer consists of a hollow, rotational cylinder, that holds the to be dried material. Hot air is introduced to the rotating chamber to ensure an evenly distributed heat distribution within. The cylinder is mounted in a slight angle so that the material moves along the length of the dryer (Figure 20).

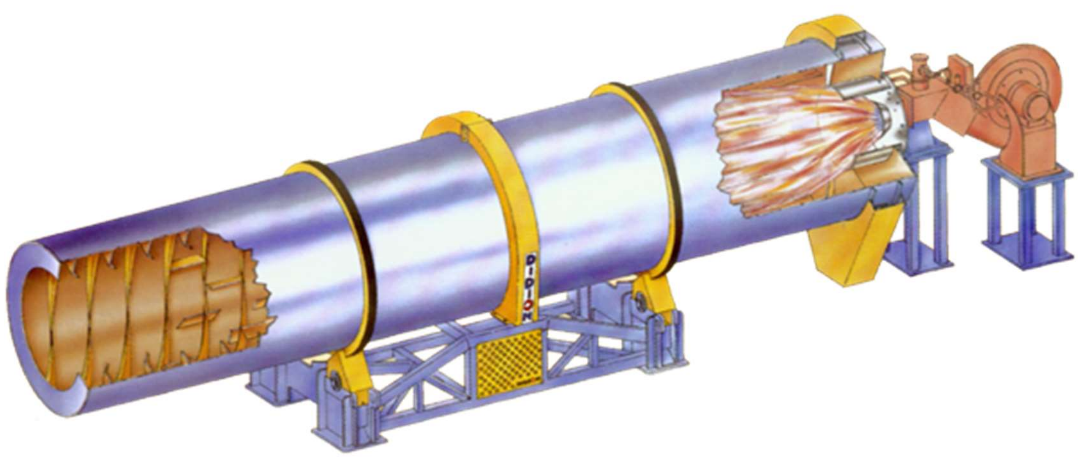

Figure 20. Rotary drum dryer (Didion, 2014)

Component D - Milling/Blending Module

Uniform size reduction is important for pretreatment of biomass. This treatment step increases the particle size as well as the pore size of the feedstock (Drzymala, 1993). A commonly used method is to shred or crush material into

smaller particles for the different application across industries. A ‘hammermill’ (Figure 21) is common and operation depends on the feedstock’s properties such as moisture content, initial particle size, ash contamination, and operational throughput (Mani *et al.*, 2004). In the bio-depot concept a multi-feedstock system is introduced that blends loblolly pine and Switchgrass.

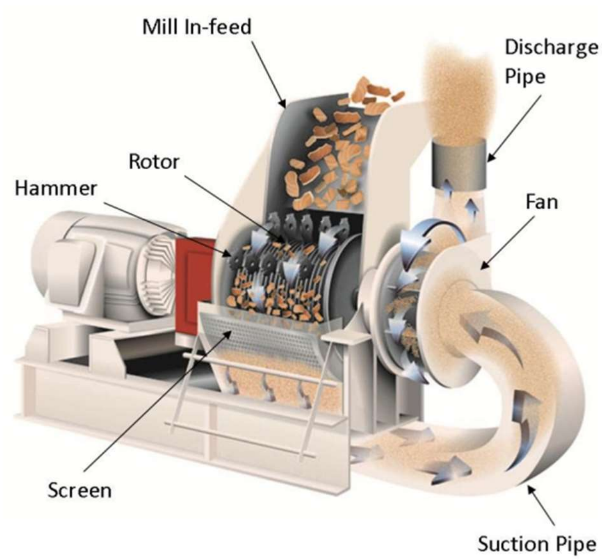

Figure 21. Display of pneumatic hammer mill (Brown, 2012).

Component E - Densification Module

Component E deals with the densification of the feedstock. Its purpose is to upturn the bulk and energy density, permitting an optimized transportation process, storage, and increases the energy output per bushel for refining purposes (Miao *et al.*, 2013). Raw biomass varies in shape and energy content significantly.

Biomass densifications processes have been adapted from highly productive and efficient industries, such as food and pharmacy. The application of pellet mills (Figure 22), briquette press, and screw extruder have been the most common machinery in use for bioenergy densification (Tumuluru *et al.*, 2011).

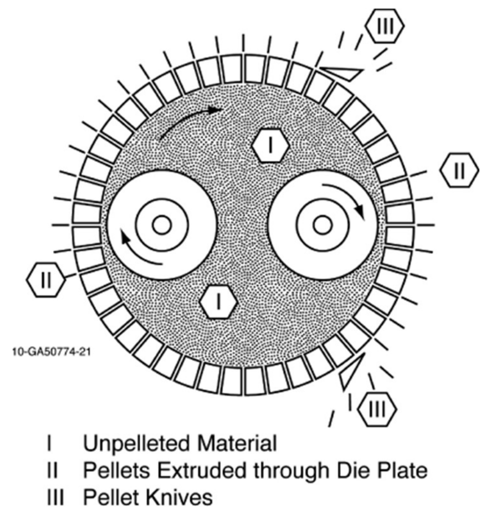

Figure 22. Display of working process of a pellet mill die (Tumuluru *et al.*, 2011).

Densification of raw biomass increases the energy content of per unit weight. This gives the feedstock an advantage to compete against with oil, and other fuels. Converted biomass pellets are graded in British thermal unit per pound (BTU/lbs.) (Sjoding *et al.*, 2013).

Simulation

A simulation of the components of the bio-depot for the knife-ring module, drying module, milling/blending module, and densification module was conducted

given the absence of data from the larger research project which was delayed. A Microsoft Excel template with simulation of the variability was developed as part of this thesis and may be useful tool for the practitioner.

Simulation of Three Key Metrics of the Bio-depot

Ash Content

Biomass combustion and its quality depends on the chemical composition. The quality of biomass is also influenced by moisture content, ash contents, species, origin, harvesting method, on site handling, logistics, pretreatment, processing, and blending (Rector *et al.*, 2013). Ash content of wood flakes stays in direct connection with bark content. Bark contains highest ash content of a tree. Ash is the inorganic matter that consists of a wide range of elements (James *et al.*, 2012). The inorganic matter is of great importance, concerning the effect on the combustion process and the impact on the biofuel plant. Supply management and harvesting methods have direct influence on the quality of the biomass and therefore for example, ash content (Obernberger *et al.*, 1997). Ash content in woody biomass, depending on the origin, ranges from 0.5 to three percent dry weight. However, ash content can rise up to ten percent, if limbs, branches, and bark are taken into account (Sjoding *et al.*, 2013).

Particle Size

Switchgrass and loblolly pine in the bio-depot are processed to generate a target particle size. The target size will be set by the market, and requirements of biorefineries. The intermediate step of “milling” is required to accomplish this task, *i.e.,* the biomass is milled to meet a target. Particle size of the raw material is a key metric due to its effect on overall feedstock quality.

Moisture Content

Feedstock moisture is a problematic and cost intensive factor, affecting feedstock supply and bio refinery performance excellence (Nigam *et al.*, 2011). Excessive moisture content can lead to an increase of dry matter loss, increased transportation cost, and spontaneous combustion during storage. Process steps like milling are negatively affect due to increased moisture in the feedstock. The high water content causes wear and tear on machinery (Mani *et al.*, 2004). Moisture content of roundwood after logging is estimated at 50% (Lu *et al.*, 2015), whereas for Switchgrass moisture content ranges from 15%-30%, depending on the season (Robert B. Mitchel, 2012). Target value for the mixed feedstock will be ten percent in the bio-depot concept presented in this thesis

Statistical Process Control

Statistical process control (SPC) procedures are suitable for monitoring a process behavior. SPC is a tool that deals with variation in a process. Variation is

unavoidable but controllable. Controlled variation is a consistent and stable pattern in process variation. On the other hand, uncontrolled variation is variation that changes due to special events or circumstances (Berger, 1986). Deming and Juran developed SPC into a tool for management to analyze variation and therefore, reduce defects. SPC is a tool to quantify variation and initiate the focus on root cause analysis (Grant *et al.*, 1994). To monitor and avoid unwanted variance, SPC provides six tools:

Control Charts:

Control Charts also known as Shewhart charts are used to evaluate data to control the stability of a process. Control charts indicate if a process changes significantly

Cause-and-Effect Diagram:

The Cause-and-Effect Diagram, also known as Ishikawa-, or Fishbone-Diagram, invented by Kaoru Ishikawa in the 1960s, is a visualization tool. Ishikawa's diagram (Figure 23) maps a process and its possible causes of a problem (Young, 2015). Important for the application of the diagram is conformity within the group that is working on finding the reason of variation in a process. The issue has to be addressed and symbolized as the "head of the fish." Every "crest" represents a major category/department. By adding subcategories, reasons for variance can be addressed more easily (Young, 2015).

Pareto Charts:

The Pareto Chart, named after Italian economist Vilfredo Pareto, is another simple tool used to graph data. This chart type, however, has the same basic structure as the histogram but also includes a cumulative percent line graph. Based on the Pareto principle, Pareto Charts are used to find the problems with the greatest potential for improvement. The Pareto Principle states that 80% of the effects are due 20% of causes. By applying this chart, most influencing causes can be addressed and improved (Wheeler *et al.*, 2010).

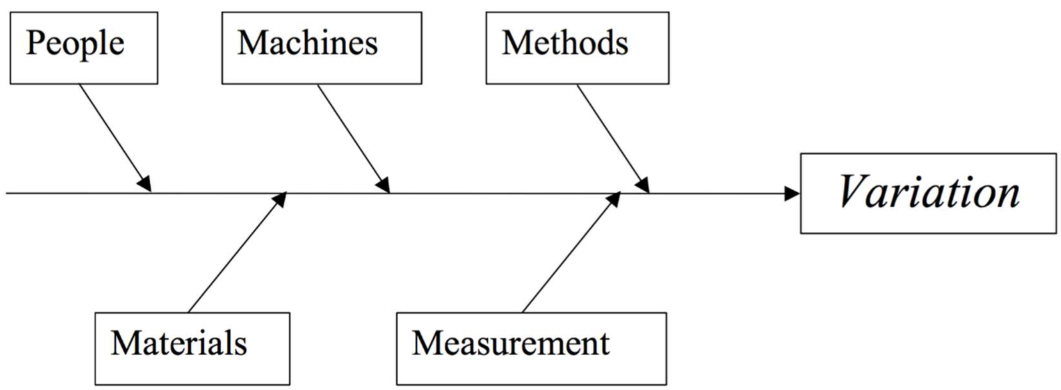

Figure 23. Example “Cause Effect- /Fishbone- / Ishikawa-Diagram” (Montgomery, 2009).

Probability Plots:

These tools are essential for the improvement and understanding approach of a manufacturing process. SPC’s main goal is the identification of variability caused by assignable causes focusing on:

Making the process stable

Minimizing the process variability

Improving the process performance (Young, 2015).

Taguchi Loss Function

Increased competition in manufacturing caused producers to focus their effort of improvement towards high quality. The origin of Taguchi Methods comes from Japan. Taguchi methods are widely used in the modern quality philosophy known as “Six-Sigma Quality.”

Taguchi believed that companies view economic loss incorrectly. That is, he believed companies greatly underestimate economic loss when they view loss that only comes from a product being out of specification. Taguchi believed that loss occurs whenever a product varies from its target. Therefore loss is directly a function of the variability of the product, *i.e.,* more variability from the target equates to more loss (Ross, 1996). Theoretically loss is zero if the target and measured value are the same (Figure 24) (Liao, 2010).

There are three types of loss functions according to Taguchi. A two-sided loss function is “nominal-is-best” when a lower and an upper specification exists. One-sided loss functions where “smaller-is-better” for a lower specification only, or “larger-is-better” for an upper specification only. Operational targets are directly related to the amount of product variation (Liao, 2010). Taguchi’s two-sided loss function is a valuable tool to address and measure the qualitative loss of one product. The two sided loss function is determined by the formula:

$$L(y) = k * (y - m)^2 \quad [4]$$

where:

L = loss in dollars when the quality characteristic is equal to y,

y = the value of the quality characteristic (*e.g.,* moisture, ash content, density, etc.),

m = target value of y,

k = constant depending on the organization's loss definition.

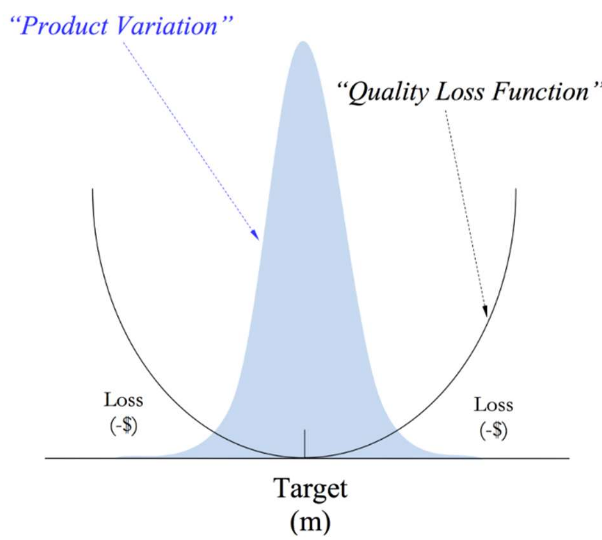

Figure 24. Two-sided Taguchi Loss Function (Taguchi *et al.*, 2004)

In addition to nominal-is-best loss function, Taguchi also provided one-sided versions for either lower or upper specifications (Liao, 2010). The smaller-the-function assumes an ideal target value as close to lower specification limit as possible (Figure 25). For example, weight in particleboard or oriented strand

board. The smaller-the-better loss function does not include negative data (Taguchi *et al.*, 2004).

The smaller-the-better loss function is defined as:

$$L(y) = k * y^2 \qquad [5]$$

where:

$$k = \frac{A_0}{y_0^2}$$

L = loss in dollars when the quality characteristic is equal to y,

k = constant depending on the organization's loss definition,

A_0 = *consumer loss,*

y_o= consumer tolerance,

y= the value of the quality characteristic (*e.g.*., moisture, ash content, density, etc.).

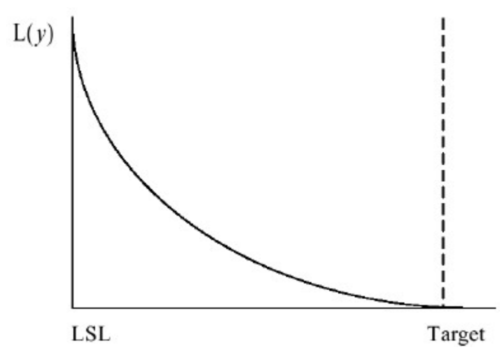

Figure 25. One-sided Taguchi Loss Function – Smaller the Better (Liao, 2010).

The larger-the-better loss function is illustrated in Figure 26. Characteristics of a larger-the-better loss function are when an upper specification is a limiting factor. An example of this is formaldehyde (HCHO) emissions from medium density fiberboard or particleboard. Theoretically if a manufacturer had no variability in HCHO emissions, they would emit at the upper specification limit. Manufacturers have to run the target emissions lower than upper specification given the degree of variability in emissions.

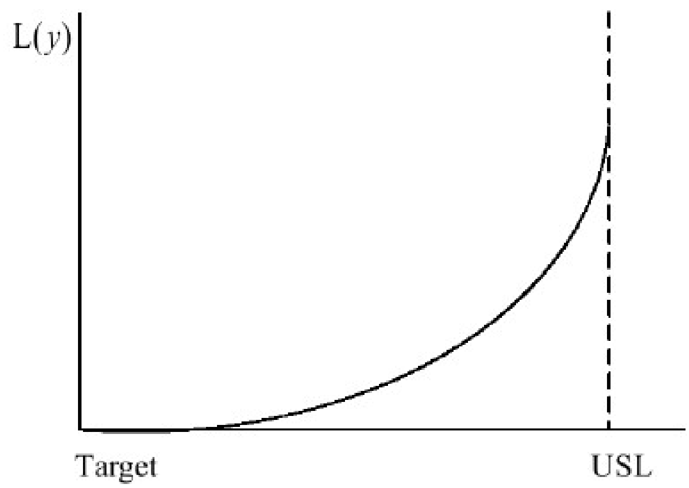

Figure 26. One-Sided Taguchi Loss Function – Larger The Better (Liao, 2010).

Taguchi’s loss method was applied to quantify the variance within the simulated process. The particle size analysis demands for a smaller the better loss function. Smaller particle size increases drying quality and pace. Moisture content is analyzed by using the nominal is best lost function, also known as two sided loss

function. The demand for a consistent moisture content of the product is needed for the densification process and transportation. Therefore, a target value of 12% was assumed to represent a target value for biorefineries. Ash content deals with the one sided lower the better loss function. Due to the uncertain ash percentage in the feedstocks, an average value of five percent was assumed.

Reliability Block Diagrams

Advances in technology, combined with the increased demand for quality and global competition, puts pressure on manufacturers. Reliability of products that have to meet customers and international standards press for quality improvement and insurance of reliability in manufacturing processes. Technical reliability is often considered as the probability that a system of equipment or devices will perform as intended, considering certain operating conditions and specified time period (Meeker *et al.*, 1998).

Reliability block diagrams (RBD) were used in this study to illustrate how system reliability influences component and system variance in the bio-depot. That is, it is illustrated that as downtime of any component in a series system increases the variability of that component increases, *i.e.,* inertia elements associated with startup operations of machinery typically have more variability than steady-state systems (example of Second Law of Thermodynamics).

RBD illustrates and estimates reliability of a process using block diagrams and probability. The components, defined as blocks, are organized as a flow from

start to finish of the process. RBDs are organized into a flow chart of blocks of series and parallel systems; and combinations of the two (Modarres *et al.*, 2009).

In this study a RBD was developed as simple series system (Figure 27). For a RBD series system, a serial connection of components is assumed. The amount of blocks is defined as *n.* A failure of any component has a direct impact on the process, resulting in system failure (Young, 2015).

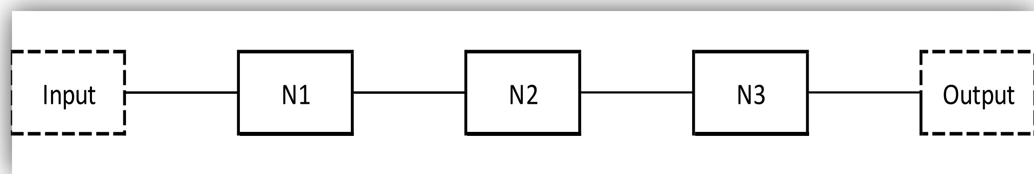

Figure 27. Reliability Block Diagram Series System.

The reliability of a series systems is expressed as:

$$R_S = R_A * R_B \ldots\ldots\ldots R_Z. \qquad [6]$$

Reliability = 1 – (failure probability). Recall all probabilities sum to 1

For example if a series system has three components (N1, N2, N3), its system reliability is illustrated as (Water, 2010):

N1 = 0.95

N2 = 0.90

N3 = 0.91

R = Reliability of process

$$R = N1 * N2 * N3 = 0.95 * 0.90 * 0.91 = 0.778$$

A parallel system is illustrated in Figure 28. If two or more blocks are active in a parallel outline all components of the system must fail simultaneously for the system to fail.

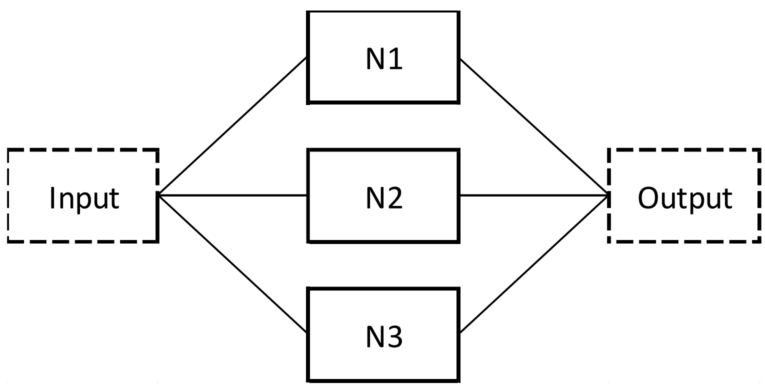

Figure 28. Reliability block diagram for a parallel system.

Failure of the entire system is defined as the principle of active redundancy.

The assumptions for a parallel model are:

- Components work independently, in view of reliability
- The system operates as long as at least one component is still operating.

For example, the reliability of a three component systems (N1, N2, N3) with full redundancy is ill-starred below Assume the components have the following reliability probabilities:

N1 = 0.95

N2 = 0.90

N3 = 0.91

R = Reliability of process

$$R = 1 - ((1 - N1) * (1 - N2) * (1 - N3))$$

$$R = 1 - \left((1 - 0.95) * (1 - 0.90) * (1 - 0.91)\right) = 0.999$$

Assuming the component's failure rates are 0.05, 0.10, 0.09 in a parallel system of three components, the overall reliability of the process equals to 99.9% (Modarres *et al.*, 2009).

CHAPTER IV. RESULTS AND DISCUSSION

Simulation Concept

The bio-depot is a concept for an intermediate step in the bio-based materials supply chain to reduce the variability of feedstock attributes which will lower costs and improve the economic competiveness of biofuels. This thesis highlights the criticality for the bioenergy industry to focus on the analytics of the supply chain as a business strategy for improved competitiveness. The idea of using analytics to improve processes and product quality is not unique, *e.g.,* Delta airlines, FEDEX, Google, Amazon, etc. This chapter illustrates the components of an Excel Workbook that was developed as template to be used for analytical support for practitioners in the bioenergy industry.

Simulation Template

Template Sheet 1 – Table of Content

The worksheet titled "Table of Contents" gives detail about the seven Excel spreadsheets included in the overall workbook (Figure 29). All hyperlinks are highlighted in blue.

Template Sheet 2 – Introduction

The second spreadsheet ("Introduction") of the workbook introduces the bio-depot concept (Figure 30). The yellow box on the top left corner of each sheet contains a hyperlink that directs the user to the Table of Contents, to enable fast

navigation throughout the workbook. A detailed view of the sheet can be found in the Appendix.

Template Sheet 3 – Flow Chart

'Template Sheet 3' is a flow chart (Figure 31) of the bio-depot. Since the bio-depot does exist yet, a series system was assumed for the simulation. The design of the bio-depot starts with the sawmill and has materials as a continuous flow starting with the receiving department, which is defined as the green framed box. BMR stands for biomass residue. The process flow is continuous with the knife-ring module, the first step for the unification of feedstock particles. The knife-ring process is assumed to create a more consistent drying process which will have lower variability in final moisture content. After this step blending and milling will be performed simultaneously. Densification then forms densified bales which are considered a final feedstock or product.

Template Sheet 4 – Reliability Block Diagram

The first section of the RBD spreadsheet includes a navigation hyperlink on the top left corner and a "Run RBD" button (Figure 32). Since there is no available data of the reliability of the components, the failure rate had to be simulated. By pressing the button, the embedded VBA code calculates failure rates for each component, as well as the systems overall reliability. This worksheet enables the user to calculate system and component reliability.

The second segment of the spreadsheet (Figure 33) highlights the process steps of the bio-depot. The different components, such as, biomass input, knife-ring module, drying module, milling module, blending module, and densification module, are displayed as P1, P2, P3, P4, P5 and P6 process steps. Given the assumption of a series system, the alignment of individual components emphasizes the systems layout. The column next to the components, indicates the reliability conditions, *i.e.,* downtime for each component in minutes. The failure reliabilities are assumed to be the downtime minutes divided by total available minutes. The consistency of the process depends on the content of downtime column boxes.

Section 3 of the RBD sheet lists the important reliability results for the reliability block diagram (Figure 34). Twenty-four hour available runtime (1440 minutes) was assumed for the runtime of this simulated process. The parameters for runtime and downtime of every stage are changeable, and recognized in the VBA code. The user can observe the overall reliability directly from the spreadsheet at the bottom of the reliability column. Reliability is presented as a percent for ease of interpretation.

On the far right of the spreadsheet a graphical display is embedded to accentuate the reliability of the modules, using a column chart (Figure 35.). Each process step is embodied by a column, the columns are split into a blue and a red section. The red section highlights the downtime. The graph automatically adapts

to changes of the calculation input. This chart is especially helpful with real data input, as failure rates of the components can be identified more easily. The chart is envisioned to be a useful tool to compare reliability at a glance.

Template Sheet 5 – Key Metrics Data Output

'Template Sheet 5' includes the data analysis output of the data implemented on 'Template Sheet 6.' The control box in white enables the user to see descriptive statistics of the variables, such as mean, standard deviation and the loss per unit. This section has key input parameters for the Taguchi loss function (Figure 36). Modifications are available by the user, such as ability to change of the lower specification limit, the target, or the k-value. Modifications are automatically calculated in the loss function. The loss function is also illustrated graphically. A hyperlink is embedded at the lower right corner of the box that directs the user to 'Template Sheet 6.' The most important aspect of this section is the display of the loss per unit calculated assuming a smaller-the-better Taguchi loss function. Below the control box a graphical display of the one-sided Taguchi loss function is displayed (Figure 37). Changing parameters in the control box or in the data will automatically be updated in this graph. The green bar emphasizes the lower specification limit; the purple bar highlights the mean of the of the data. The data distribution is displayed with the blue line, and the red line represents the change of loss when deviating from target. The third part of the chip size data analysis emphasizes the distribution and quantity of the size sections. This chart

provides information about frequency and data input. The chart automatically updates, when data inputs are changed (Figure 38). Furthermore, does this chart highlight the loss per frequency bin. The result emphasizes the loss created by the bin levels.

‘Template Sheet 5’ (Figure 39) includes the data analysis output of the data implemented in ‘Template Sheet 6.’ The control box in whites enable the user to see descriptive statistics (sample mean, sample standard deviation, and loss per unit. Modifications to this data are automatically updated in the Taguchi loss function on the output page. Modifications are capable to the upper specification limit, lower specification limit, target, or *k*-value. A hyperlink is embedded at the lower right corner of the box to navigate to “Template Sheet 6,’ namely data input for key metrics. The most important aspect of this section is the display of the loss per unit assuming the two-sided, nominal-the-best Taguchi loss function. A graphical display of the one-sided Taguchi loss function is also displayed (Figure 36). Changing parameters in the control box or in the data will automatically be presented in this graph. The green bar emphasizes the lower specification limit; dark green bar represents the upper specification limit; the purple bar highlights the mean of the data. The data distribution is displayed with the blue line, and the red line represents the change of loss when deviating from target.

The moisture content data analysis section emphasizes the distribution and quantity of the size sections (Figure 40). This chart provides information about

frequency of data input, as well as a histogram to emphasize the distribution of moisture. The chart updates when changed by the user. Furthermore, does this chart highlight the loss per frequency bin. The result emphasizes the loss created by the bin levels. The third section of the 'Template Sheet 5' (Figure 41) focuses on ash content. A one-sided loss function was assumed to determine the loss induced by the process variability. The user has the option to change, LSL, target, and *k* value. The green bar emphasizes the lower specification limit; the purple bar highlights the mean of the data. The chart allows for data entry and the control boxes automatically update.

The ash content data are illustrated as a histogram and frequency table (Figure 42). This chart provides information about frequency of the data input and is useful for the visualization of the distribution of ash content. Charts are updated automatically when data are changed.

Template Sheet 6 – Data input

'Template Sheet 6' (Figure 43) provides sections for the calculation of the two types of Taguchi loss functions, smaller-the-better, and nominal-is-best. Sample averages, standard deviations, variances, mean square deviation, and loss are automatically calculated as data is imported. The mentioned parameters are linked to 'Template Sheet 5,' and are the source for the graphical outputs. Every section of this sheet, such as particle size, moisture content, and ash content have a redirecting hyperlink embedded. The hyperlink directs the user to the output

of the data analysis. The loss function is included by every section of the data input sheet. The column “L.F./Unit” calculates the loss of every data point individually. The equation of the loss function is embedded in the column and adapts automatically to changes in the data set. Mean square deviation (MSD) for the loss per unit calculation is programmed to adapt to changes in mean and standard deviation. Column “*f(y)*” is responsible for the distribution presentation. This column interacts with the y value mean and the standard deviation.

Template Sheet 7 – Results

The ‘Results’-sheet deals with the calculated results of the Taguchi analysis, RBD, components of variance (Figure 52). The user is able to find all gathered information about the process in one sheet. This sheet should be used as a tool for detecting failures in the in the data input phase more easily. Every key metric, process step, and reliability data is listed a specified. All excel boxes are directly linked to the data entry boxes of the other sheets.

Template Sheet 8 – Help Guide

The help guide provides additional information to associated with ’Template Sheet 6’ concerning the Taguchi loss function.

Template Sheet 9 – Total Taguchi Loss Function

‘Total Taguchi Loss Function-sheet deals with the overall loss of the process and the display of the data. For that reason, a multiple1 linear regression model is applied. The user can import information to develop MLR model, estimate

model coefficients, means and standard deviations for each significant variable, and estimate the correlation coefficients for each significant variable. The output is defined by a histogram and s-bar chart (Figure 52). The user can decide whether a normal or a lognormal distribution is a better fit for the imported data. The spreadsheet calculates both nominal is best and lower the better loss function.

CHAPTER V. CONCLUSIONS AND RECOMMENDATIONS FOR IMPROVEMENT

The simulation of the bio-depot and its key metrics is a beneficial tool for the continuous preparation and planning of the conceptual bio-depot idea. The Excel workbook can be used to emphasize the measurements collected for key data associated with the bio-depot process. Reliability, variance, and loss are quantified using this workbook. Statistical process control and its tools are suitable methods for monitoring the depots process steps. In combination with the Taguchi Loss Function, financial and process relevant factors can be evaluated and addressed. When the bio-depot starts its production and data are gathered, the spread sheets will help to improve the process quality at its genesis stage. Real-time data analyses will be needed at the bio-depot to ensure process control of variation and continuous improvement.

This research will need to be validated with actual data from the bio depot. Given real data, sensitivity analyses can be conducted. This will allow the practitioner to focus on components of the bio-depot that have the poorest reliability, largest variance, and highest economic loss. This will hopefully allow for improvements of the bio-depot based on analytics. Process and business analytics are necessary to improve final product outputs (*e.g.,* biofuels, etc.) at a competitive cost.

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Zamora-Cristales, R., Sessions, J., Boston, K., & Murphy, G. (2015). Economic Optimization of Forest Biomass Processing and Transport in the Pacific Northwest USA. *Forest Science, 61*(2), 220-234. doi:10.5849/forsci.13-158

APPENDICES

Appendix A

Merchandising Depot _ Platzer	
Table of Content	
Introduction	Intro
Flow Chart	Flow Chart
Reliability Block Diagram	RBD
Key Metrics Data Output	KM
Key Metrics Data	Data
Summary of Results	Results
Help Guide	Guide
Depot Loss Function	Taguchi

Figure 29. Template Sheet 1 – table of contents.

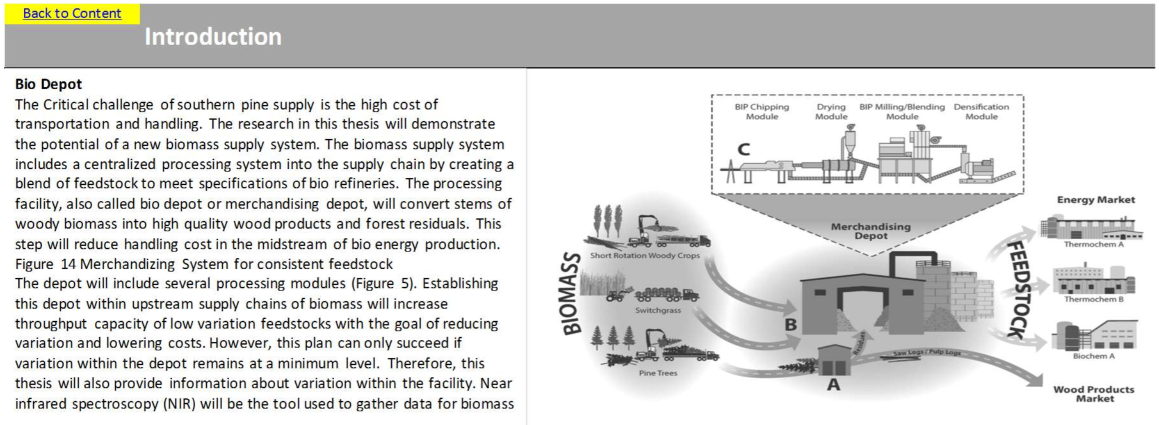


Figure 30. Template sheet 2 – introduction.

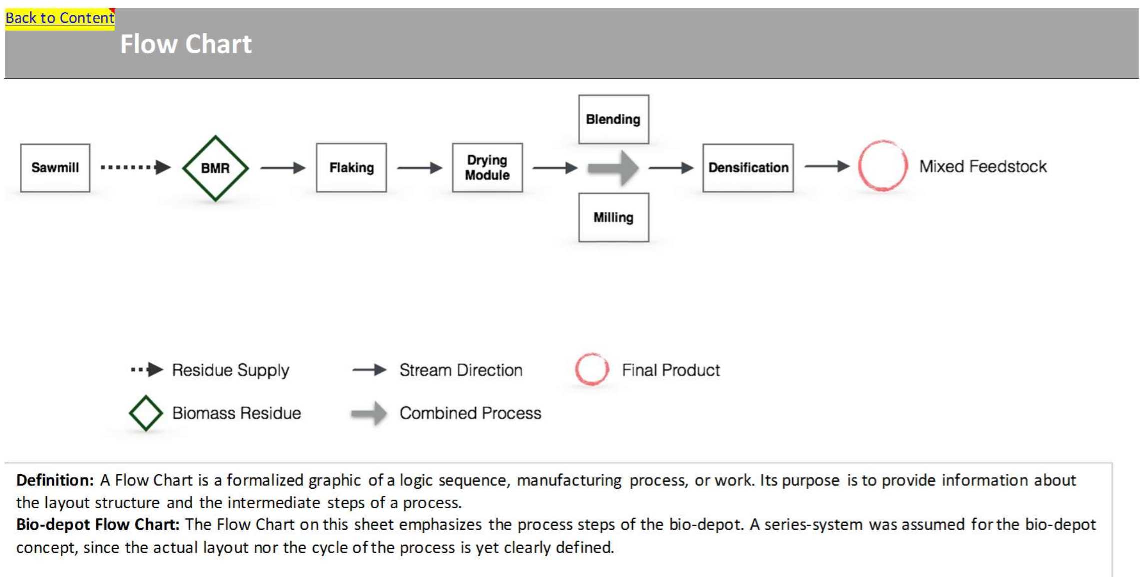


Figure 31. Template sheet 3 – flow chart.

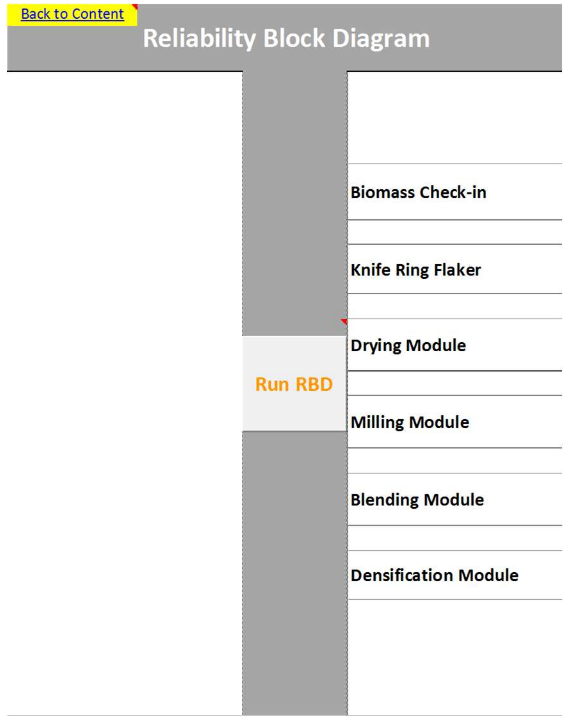


Figure 32. Template sheet 4 – reliability block diagram section 1.

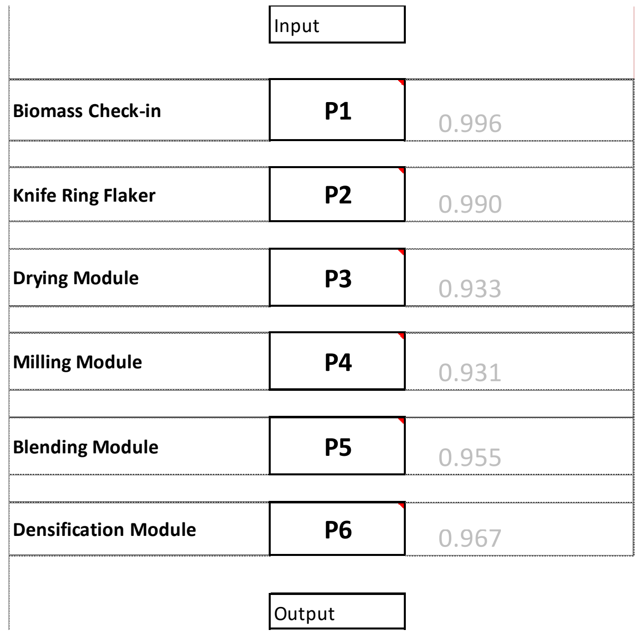


Figure 33. Template sheet 4 – reliability block diagram section 2.

Downtime (min)	Runtime (min)	Reliability (%)
6.27	1440	99.56
13.80	1440	99.04
96.55	1440	93.30
99.08	1440	93.12
64.86	1440	95.50
47.15	1440	96.73

	Overall Reliability	**77%**

Figure 34. Template sheet 4 – reliability block diagram section 3.

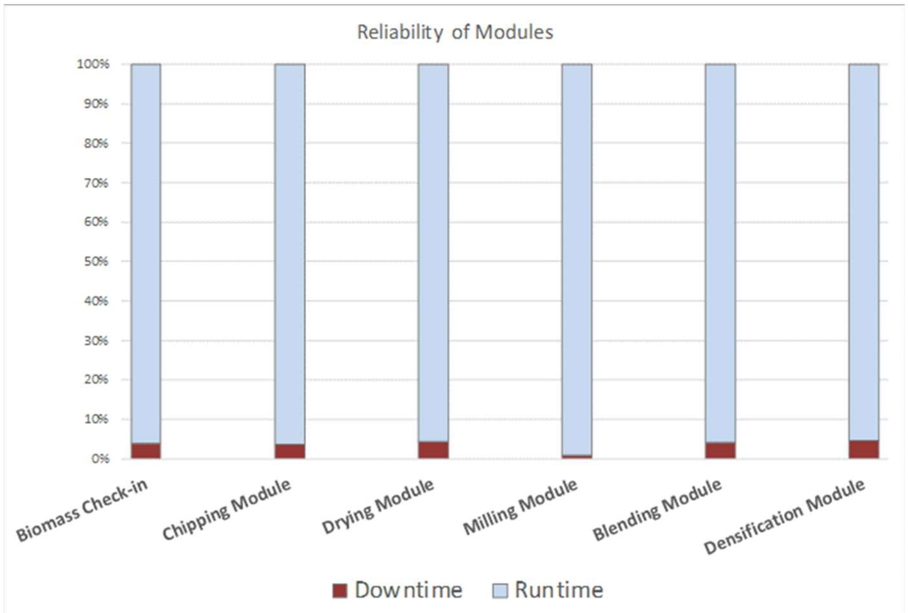


Figure 35. Template sheet 4 – reliability block diagram section 4.

	Chip Size Distribution						
Total Loss	Input			Output			
$ 50,450.03	LSL	20.1	cm	Mean	24.426825		
				Std. Dev.	18.552529		
	Target	18	cm	Loss	47.043	in $ per cm unit	
	k	0.05	$/cm^2	Total Loss	47043.31	in $	

Figure 36. Template sheet 5 – key metrics data output section 1.1 chip size.

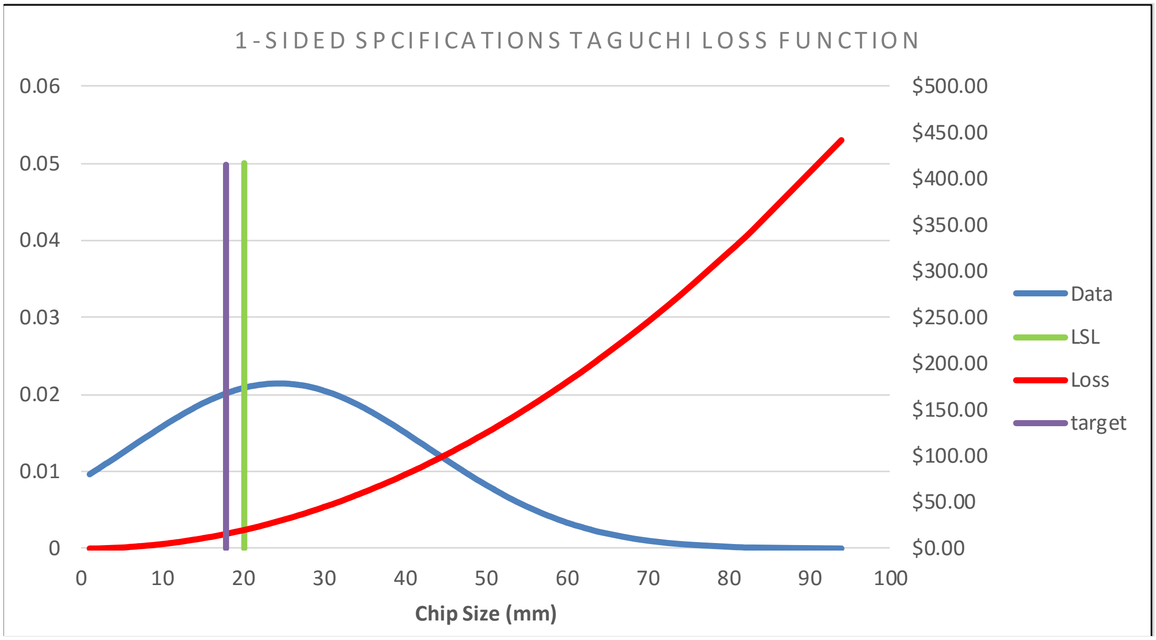
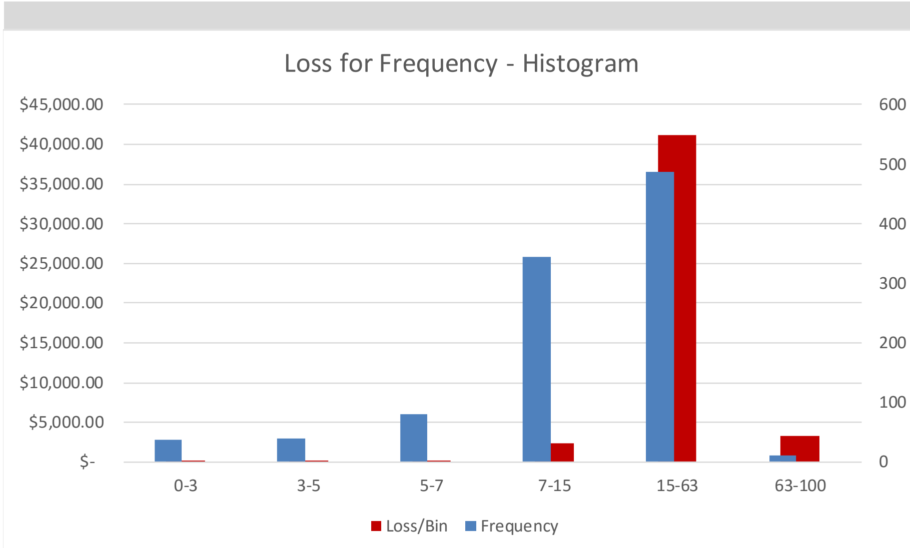


Figure 37. Template sheet 5 – key metrics data output section 1.2 chip size.



Data Frequency Intervals	Frequency		Loss/Bin
0-3	38		$ 11.55
3-5	40		$ 46.40
5-7	80		$ 183.00
7-15	344		$ 2,327.80
15-63	488		$ 41,202.60
63-100	10		$ 3,271.96
		Total Loss	**$ 47,043.31**

Figure 38. Template sheet 5 – key metrics data output section 1.3 chip size.

Moisture content

Input			Output		
USL	21	%	**Mean**	14.88239	
LSL	10	%	**Std. Dev.**	2.345716	
Target	10	%	**Loss**	2.934	in $ per % unit
k	0.1	$/%	**Total Loss**	2934.01	in $

Data

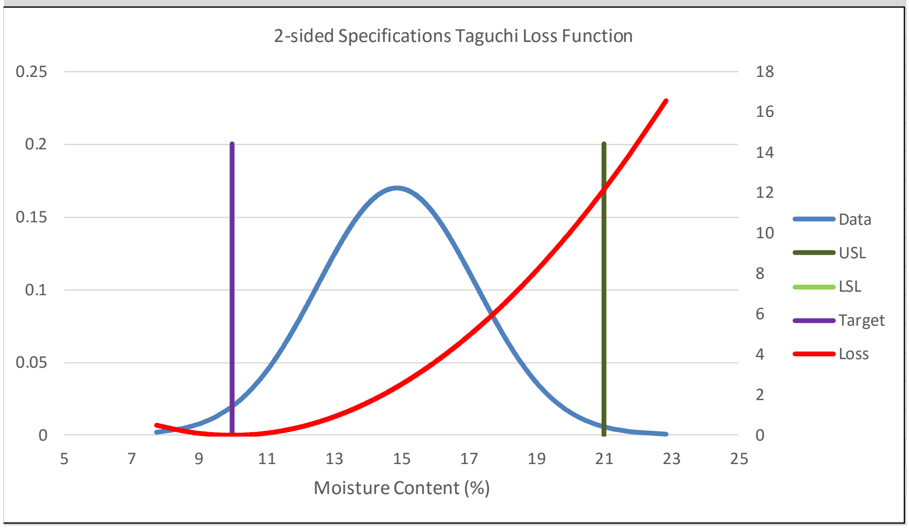
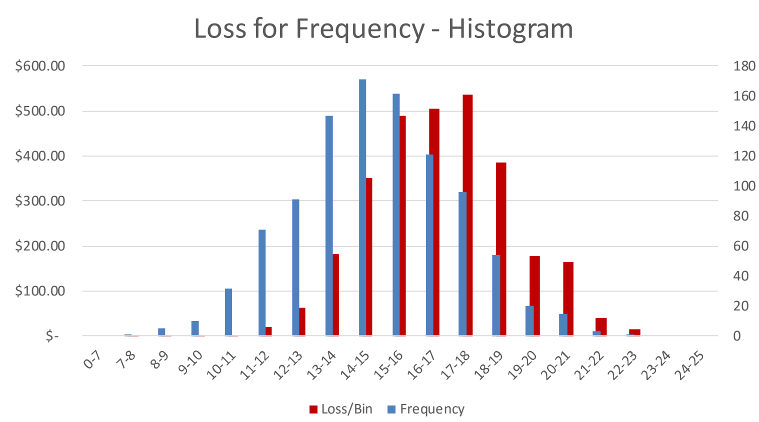


Figure 39. Template sheet 6 - key metrics data output section 2.1 moisture content.



Data Frequency Intervals	Frequency		Loss/Bin		
0-7	0		$ -		
7-8	1		$ 0.50		
8-9	5		$ 0.95		
9-10	10		$ 0.26		
10-11	32		$ 1.30		
11-12	71		$ 19.05		
12-13	91		$ 61.82		
13-14	147		$ 183.13		
14-15	171		$ 351.12		
15-16	162		$ 489.01		
16-17	121		$ 505.23		
17-18	96		$ 536.61		
18-19	54		$ 385.33		
19-20	20		$ 177.97		
20-21	15		$ 164.44		
21-22	3		$ 40.79		
22-23	1		$ 16.52		
23-24	0		$ -		
24-25	0		$ -		
		Total Loss	**$ 2,934.01**		

Figure 40. Template sheet 5 – key metrics data output section 2.2 moisture content.

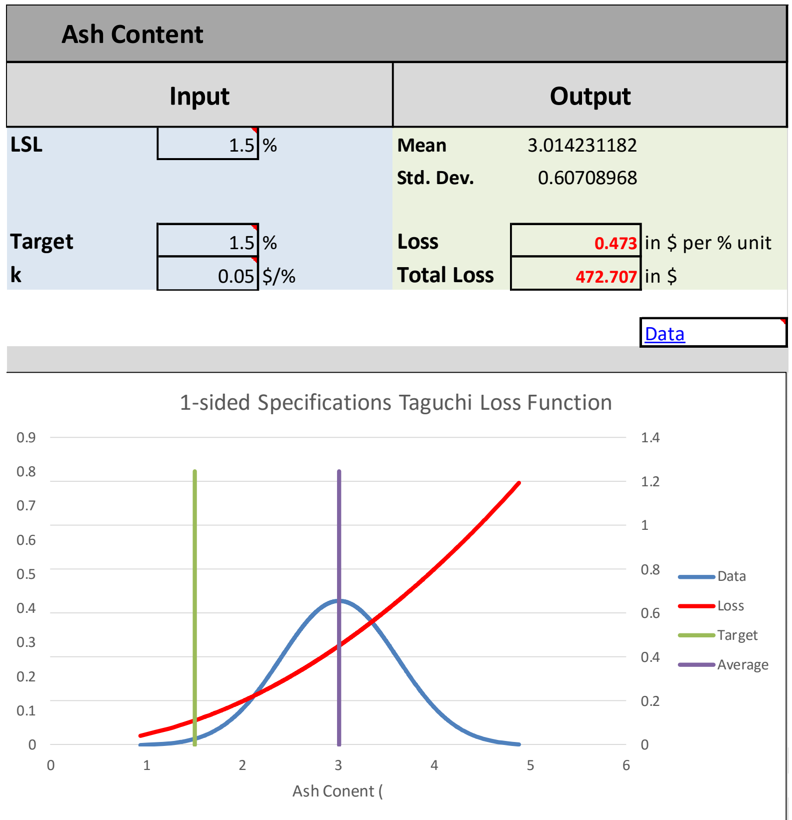
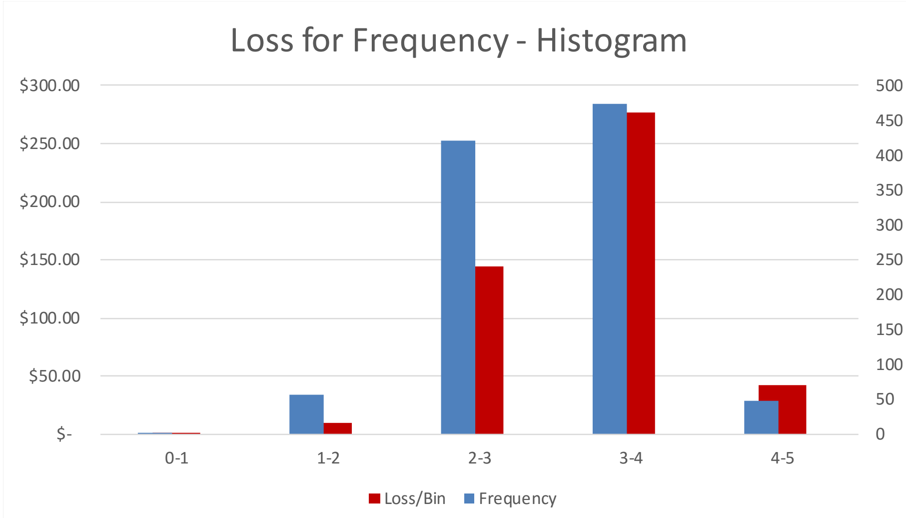


Figure 41. Template Sheet 5 – Key metrics data output section 3.1 Ash Content.



Data Frequency Intervals	Frequency		Loss/Bin
0-1	1		$ 0.04
1-2	56		$ 9.25
2-3	421		$ 144.52
3-4	474		$ 277.14
4-5	48		$ 42.16
	0		$ -
		Total Loss	**$ 473.11**

Figure 42. Template Sheet 5 – Key metrics data output section 3.2 Ash Content.

f(y)	y	L.F./Unit	Average	Standard Deviation
0.009689	1	0.05	24.4	18.55252878
0.009689	1	0.05		Sigma^2
0.009689	1	0.05	596.67	344.20
0.009689	1	0.05		MSD
0.009689	1	0.05		940.87
0.009689	1	0.05		Loss PS
0.009689	1	0.05		47.04330534

Figure 43. Template Sheet 6 – key metrics data input.

Appendix B

Merchandising Depot _ Platzer

Table of Content

Introduction	Intro
Flow Chart	Flow Chart
Reliability Block Diagram	RBD
Key Metrics Data Output	KM
Key Metrics Data	Data
Help Guide	Guide
Depot Loss Function	Taguchi

Figure 44. Excel workbook: sheet 1, table of content for spread sheet.

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Introduction

Bio Depot

The Critical challenge of southern pine supply is the high cost of transportation and handling. The research in this thesis will demonstrate the potential of a new biomass supply system. The biomass supply system includes a centralized processing system into the supply chain by creating a blend of feedstock to meet specifications of bio refineries. The processing facility, also called bio depot or merchandising depot, will convert stems of woody biomass into high quality wood products and forest residuals. This step will reduce handling cost in the midstream of bio energy production.
Figure 14 Merchandizing System for consistent feedstock
The depot will include several processing modules (Figure 5). Establishing this depot within upstream supply chains of biomass will increase throughput capacity of low variation feedstocks with the goal of reducing variation and lowering costs. However, this plan can only succeed if variation within the depot remains at a minimum level. Therefore, this thesis will also provide information about variation within the facility. Near infrared spectroscopy (NIR) will be the tool used to gather data for biomass

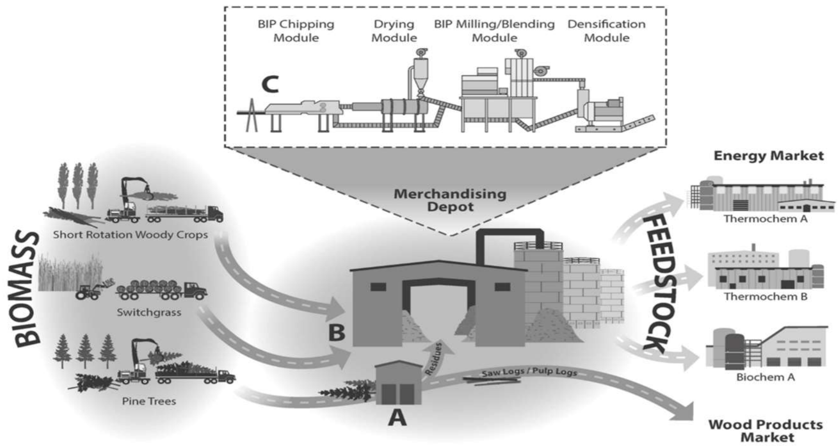

Figure 45. Excel workbook: sheet 1, introduction to Bio-depot.

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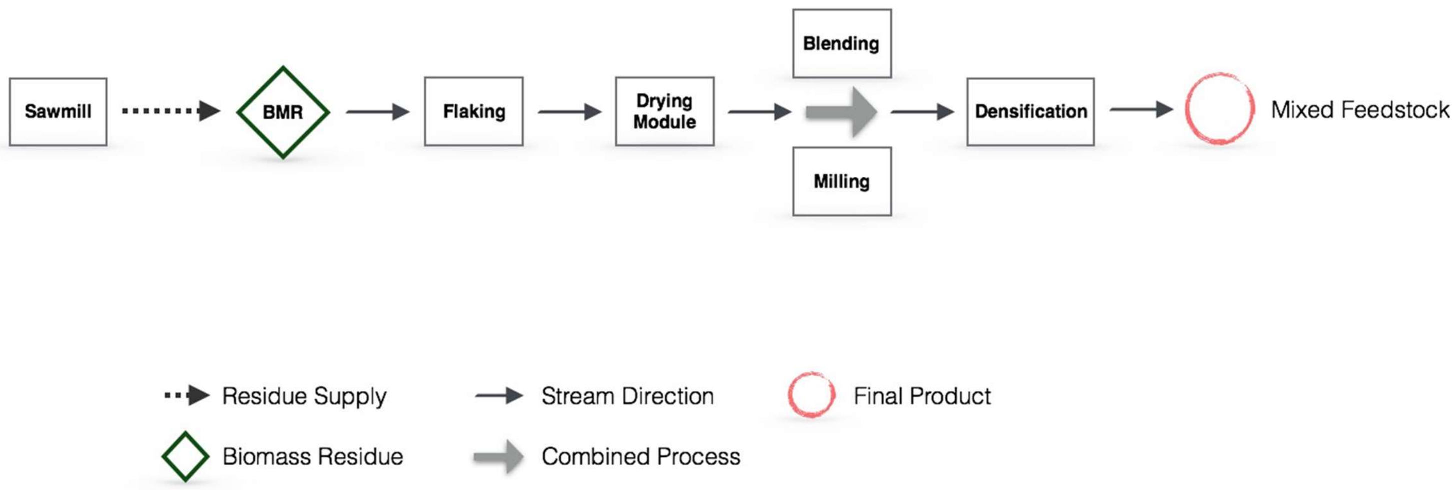
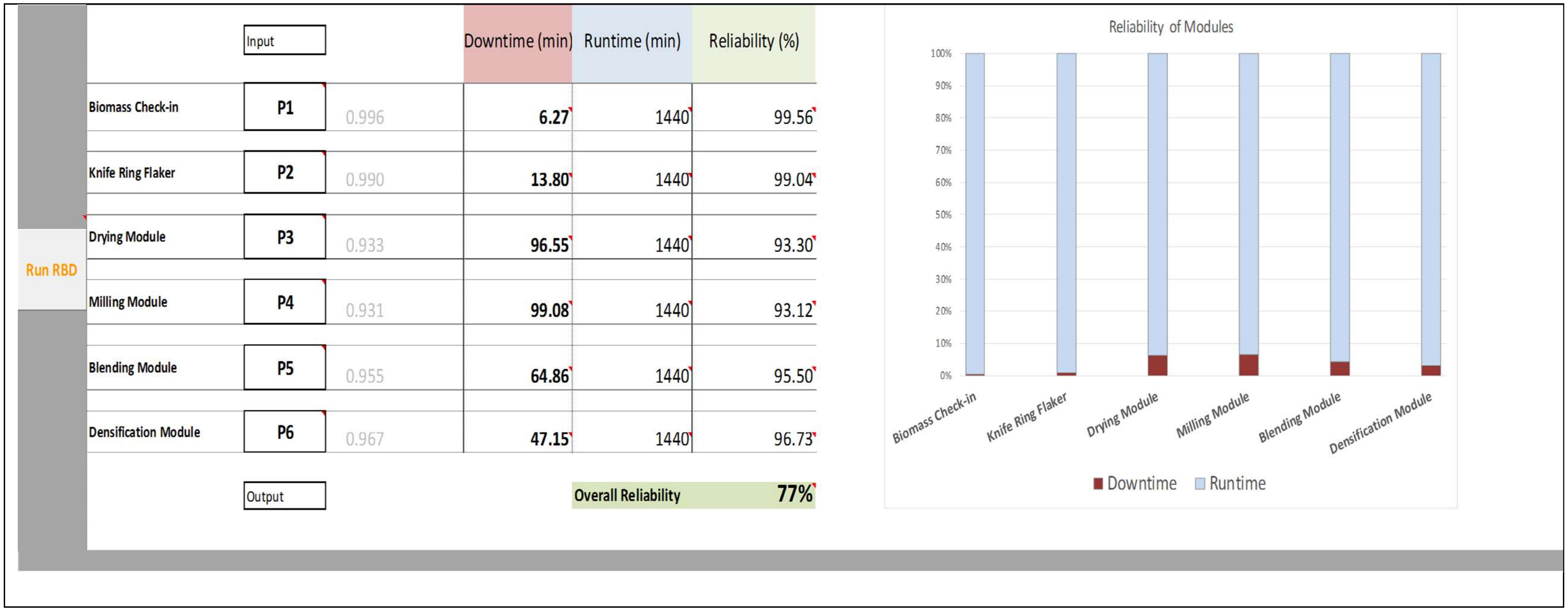
Flow Chart



Definition: A Flow Chart is a formalized graphic of a logic sequence, manufacturing process, or work. Its purpose is to provide information about the layout structure and the intermediate steps of a process.
Bio-depot Flow Chart: The Flow Chart on this sheet emphasizes the process steps of the bio-depot. A series-system was assumed for the bio-depot concept, since the actual layout nor the cycle of the process is yet clearly defined.

Figure 46. Excel workbook: sheet 3, flow chart for Bio-depot.



			Downtime (min)	Runtime (min)	Reliability (%)
	Input				
Biomass Check-in	P1	0.996	6.27	1440	99.56
Knife Ring Flaker	P2	0.990	13.80	1440	99.04
Drying Module	P3	0.933	96.55	1440	93.30
Milling Module	P4	0.931	99.08	1440	93.12
Blending Module	P5	0.955	64.86	1440	95.50
Densification Module	P6	0.967	47.15	1440	96.73
	Output			Overall Reliability	77%

Figure 47. Excel workbook: sheet 4, Reliability Block Diagram.

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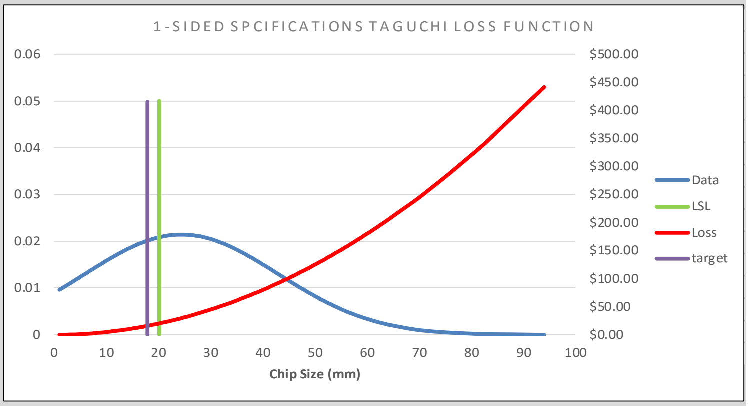
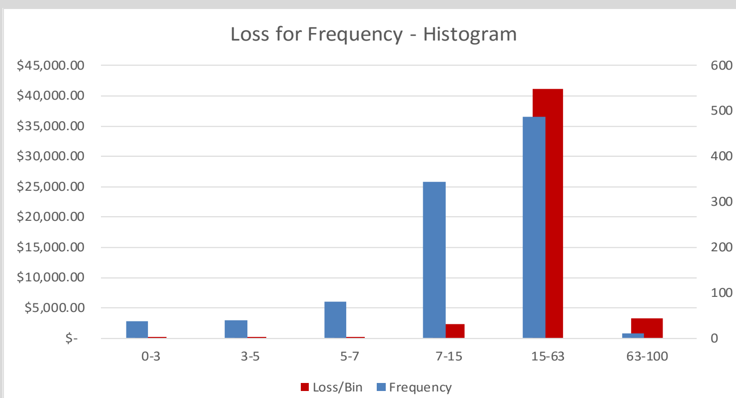
Taguchi Loss Function for Key Metrics

Chip Size Distribution

Total Loss	Input			Output		
$ 50,450.03	LSL	20.1	cm	Mean	24.426825	
				Std. Dev.	18.552529	
	Target	18	cm	Loss	47.043	in $ per cm unit
	k	0.05	$/cm^2	Total Loss	47043.31	in $

Data





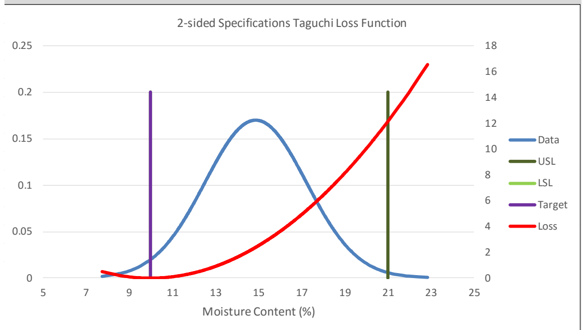
Data Frequency Intervals	Frequency		Loss/Bin
0-3	38		$ 11.55
3-5	40		$ 46.40
5-7	80		$ 183.00
7-15	344		$ 2,327.80
15-63	488		$ 41,202.60
63-100	10		$ 3,271.96
		Total Loss	$ 47,043.31

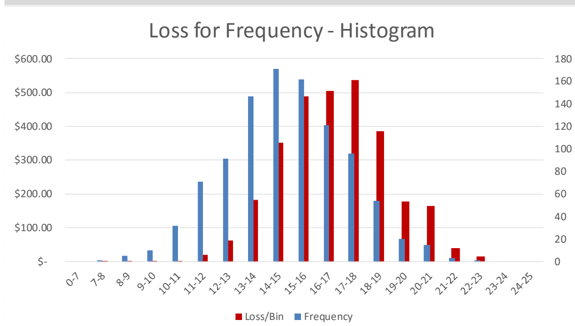
Figure 48. Excel workbook: sheet 5.1, Taguchi Loss Function for chip size.

Moisture content

Input			Output		
USL	21	%	Mean	14.88239	
LSL	10	%	Std. Dev.	2.345716	
Target	10	%	Loss	2.934	in $ per % unit
k	0.1	$/%	Total Loss	2934.01	in $

Data





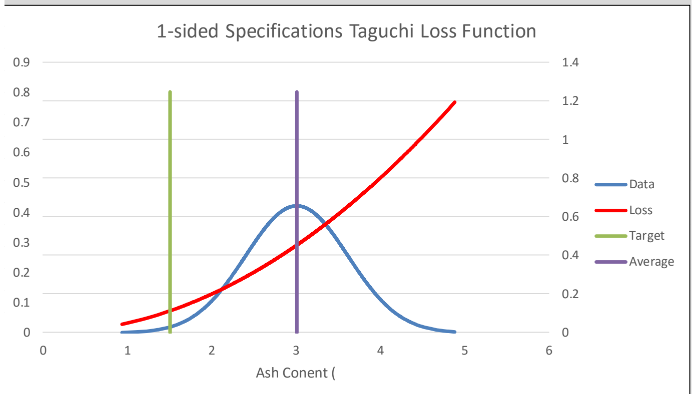
Data Frequency Intervals	Frequency		Loss/Bin
0-7	0		$ -
7-8	1		$ 0.50
8-9	5		$ 0.95
9-10	10		$ 0.26
10-11	32		$ 1.30
11-12	71		$ 19.05
12-13	91		$ 61.82
13-14	147		$ 183.13
14-15	171		$ 351.12
15-16	162		$ 489.01
16-17	121		$ 505.23
17-18	96		$ 536.61
18-19	54		$ 385.33
19-20	20		$ 177.97
20-21	15		$ 164.44
21-22	3		$ 40.79
22-23	1		$ 16.52
23-24	0		$ -
24-25	0		$ -
		Total Loss	$ 2,934.01

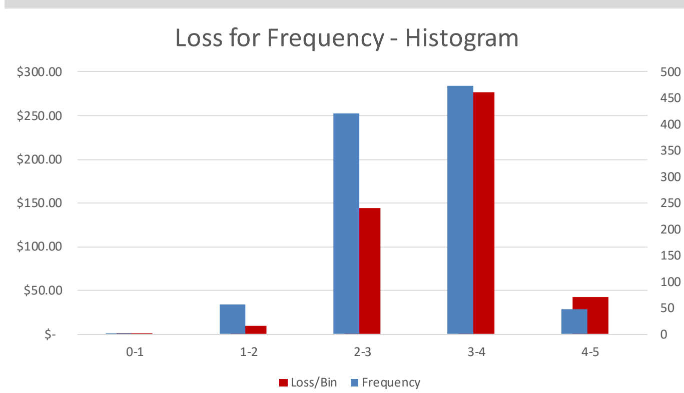
Figure. 49 Excel workbook: sheet 5.2, Taguchi Loss Function for moisture content.

Ash Content

Input			Output		
LSL	1.5	%	**Mean**	3.014231182	
			Std. Dev.	0.60708968	
Target	1.5	%	**Loss**	0.473	in $ per % unit
k	0.05	$/%	**Total Loss**	472.707	in $

Data





Data Frequency Intervals	Frequency		Loss/Bin
0-1	1		$ 0.04
1-2	56		$ 9.25
2-3	421		$ 144.52
3-4	474		$ 277.14
4-5	48		$ 42.16
	0		$ -
		Total Loss	**$ 473.11**

Figure 50. Excel workbook: sheet 5.3, Taguchi Loss Function for ash content.

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Dataset for Keymetrics

Overall variance
1295.904154

Particle Size Data

Output

f(y)	y	L.F./Unit	Average	Stndard Deviation		
0.009689	1	0.05	24.4	18.55252878		
0.009689	1	0.05		Sigma^2		
0.009689	1	0.05	596.67	344.20		
0.009689	1	0.05		MSD		
0.009689	1	0.05		940.87		
0.009689	1	0.05		Loss PS		
0.009689	1	0.05		47.04330534		
0.010356	2	0.2		Total Loss		
0.010356	2	0.2		47043.30534		
0.010356	2	0.2				
0.010356	2	0.2				
0.010356	2	0.2				
0.010356	2	0.2		avaerage/6sigma	Sum	
0.010356	2	0.2		0.219438415	2.10436337	
0.010356	2	0.2		Weighted Variance		
0.010356	2	0.2		0.104277815		
0.010356	2	0.2				
0.010356	2	0.2				
0.011037	3	0.45				
0.011037	3	0.45		**Data Frequency**		
0.011037	3	0.45		**Intervals**	**Bins**	**Frequency**
0.011037	3	0.45		0-3	3	38
0.011037	3	0.45		3-5	5	40
0.011037	3	0.45		5-7	7	80
0.011037	3	0.45		7-15	15	344
0.011037	3	0.45		15-63	63	488
0.011037	3	0.45		63-100	100	10
0.011037	3	0.45				0
0.011037	3	0.45				
0.011037	3	0.45				
0.011037	3	0.45		**Bins/Intervals**		**Loss/Bin**
0.011037	3	0.45		**0**	3	$ 11.55
0.011037	3	0.45		3	5	$ 46.40
0.011037	3	0.45		5	7	$ 183.00
0.011037	3	0.45		7	15	$ 2,327.80
0.011037	3	0.45		15	63	$ 41,202.60
0.011037	3	0.45		63	100	$ 3,271.96
0.011037	3	0.45			Total Loss	**$ 47,043.31**
0.011729	4	0.8				
0.011729	4	0.8				
0.011729	4	0.8				
0.011729	4	0.8				
0.011729	4	0.8				
0.011729	4	0.8				
0.011729	4	0.8				
0.011729	4	0.8				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				
0.012428	5	1.25				

Moisture Content Data

Output

f(y)	y	L.F./Unit	Average	Stndard Deviation		
0.001714	7.769598	0.497469345	14.88239	2.345716155		
0.004217	8.503762	0.2238728		Sigma^2		
0.004486	8.557477	0.208087211		5.502384279		
0.004687	8.595673	0.197213524		(yhat-m)^2		
0.004753	8.608002	0.193765802		23.83776461		
0.006516	8.890977	0.12299331		MSD		
0.007812	9.059925	0.08837414		29.34014889		
0.009016	9.196972	0.064485455		Loss MC		
0.010822	9.376568	0.038866733		2.934014889		
0.01197	9.478222	0.02722527		Total Loss		
0.012522	9.524349	0.022624354		2934.014889		
0.013442	9.59768	0.016186175				
0.017237	9.863281	0.001869221		avaerage/6sigma	Sum	
0.017564	9.883909	0.001347719		1.057416467	2.104363	
0.018079	9.91581	0.000708793		Weighted Variance		
0.019179	9.981704	3.34749E-05		0.5025		
0.020424	10.05284	0.000279158				
0.021341	10.10312	0.001063442				
0.022068	10.14184	0.002011749				
0.023378	10.20926	0.004378985		**Data Frequency**		
0.023913	10.23597	0.005568039		**Intervals**	**Bins**	**Frequency**
0.024646	10.27188	0.007391743		0-7	7	0
0.025998	10.33605	0.011292752		7-8	8	1
0.026717	10.36918	0.013629164		8-9	9	5
0.026914	10.37817	0.014300908		9-10	10	10
0.027013	10.38265	0.014642015		10-11	11	32
0.027725	10.41457	0.017186982		11-12	12	71
0.028481	10.44781	0.020053353		12-13	13	91
0.029135	10.47607	0.022664106		13-14	14	147
0.029424	10.48844	0.023857454		14-15	15	171
0.030312	10.52582	0.027648387		15-16	16	162
0.030694	10.54165	0.029338418		16-17	17	121
0.030908	10.55048	0.030302414		17-18	18	96
0.032419	10.61152	0.037395685		18-19	19	54
0.033027	10.63553	0.040390145		19-20	20	20
0.035861	10.74357	0.055289068		20-21	21	15
0.035906	10.74526	0.055540988		21-22	22	3
0.036428	10.76451	0.05844708		22-23	23	1
0.036632	10.77196	0.059592987		23-24	24	0
0.038405	10.83574	0.069845379		24-25	25	0
0.038872	10.8522	0.072625083				0
0.03905	10.85843	0.073690708				
0.039293	10.86694	0.075157868		**Bins/Intervals**		**Loss/Bin**
0.040766	10.91769	0.084215068		**0**	7	$ -
0.041463	10.94129	0.088602768		7	8	$ 0.50
0.041507	10.94276	0.08887892		8	9	$ 0.95
0.042695	10.98239	0.096508046		9	10	$ 0.26
0.043039	10.99371	0.098746404		10	11	$ 1.30
0.044171	11.03061	0.106216615		11	12	$ 19.05
0.045187	11.06325	0.113049793		12	13	$ 61.82
0.045503	11.07329	0.115195873		13	14	$ 183.13
0.045566	11.0753	0.115626583		14	15	$ 351.12
0.047215	11.12704	0.127022109		15	16	$ 489.01
0.050593	11.22968	0.151210086		16	17	$ 505.23
0.052079	11.27355	0.162193051		17	18	$ 536.61
0.052139	11.27531	0.162640818		18	19	$ 385.33
0.052418	11.28345	0.164725646		19	20	$ 177.97
0.052955	11.29906	0.168755878		20	21	$ 164.44
0.053034	11.30136	0.169352832		21	22	$ 40.79
0.053568	11.31679	0.173393521		22	23	$ 16.52
0.054159	11.33375	0.177889851		23	24	$ -
0.054531	11.3444	0.180741599		24	25	$ -
0.055137	11.36162	0.185402043			Total Loss	**$ 2,934.01**

Ash Content Data

Output

f(y)	y	L.F./Unit	Average	Standard Deviation		
0.001957	0.94364	0.044522799	3.014231	0.60708968		
0.00904	1.236744	0.076476839		Sigma^2		
0.016362	1.36435	0.09307257	9.09	0.37		
0.018006	1.385872	0.096032124		MSD		
0.029106	1.498461	0.112269213		9.45		
0.032224	1.52341	0.116038884		Loss Ash		
0.038184	1.565974	0.122613766		0.472707375		
0.044903	1.607829	0.129255734		Total Loss		
0.046176	1.615174	0.130439395		472.7073748		
0.04836	1.627398	0.132421192				
0.05468	1.660434	0.137852113				
0.059099	1.68176	0.141415867				
0.059099	1.68176	0.141415867		avaerage/6sigma	Sum	
0.059318	1.682786	0.141588453		0.827508488	2.104363	
0.059757	1.684827	0.141932102		Weighted Variance		
0.059865	1.685329	0.1420167		0.3932346		
0.062475	1.697214	0.144026823				
0.066131	1.713231	0.146757942				
0.067623	1.719566	0.147845373				
0.068047	1.721345	0.148151437		**Data Frequency**		
0.071215	1.734382	0.150404		**Intervals**	**Bins**	**Frequency**
0.080931	1.771757	0.156956056		0	0	0
0.085177	1.78702	0.159671961		0-1	1	1
0.08598	1.789841	0.160176523		1-2	2	56
0.087281	1.79437	0.160988218		2-3	3	421
0.094393	1.818272	0.1653056		3-4	4	474
0.096636	1.825529	0.166627893		4-5	5	48
0.102036	1.842512	0.169742442				0
0.102992	1.845447	0.170283807				
0.104706	1.850664	0.171247912		**Bins/Intervals**		**Loss/Bin**
0.11723	1.887019	0.178041958		0	1	$ 0.04
0.117598	1.888045	0.178235602		1	2	$ 9.25
0.120161	1.895122	0.179574406		2	3	$ 144.52
0.120891	1.897119	0.179953108		3	4	$ 277.14
0.128291	1.916895	0.183724416		4	5	$ 42.16
0.128291	1.916895	0.183724416		5	6	$ -
0.128738	1.918063	0.183948338			Total Loss	**$ 473.11**
0.131143	1.924303	0.185147165				
0.132118	1.926811	0.185629994				
0.133356	1.929979	0.186240865				
0.133621	1.930653	0.186370956				
0.14019	1.9471	0.189559884				
0.141663	1.950718	0.190264993				
0.14175	1.950931	0.190306511				
0.142529	1.95283	0.190677178				
0.143823	1.955973	0.191291488				
0.148108	1.966248	0.193306621				
0.150743	1.972469	0.194531748				
0.151759	1.974848	0.195001329				
0.153699	1.979361	0.195893579				
0.155211	1.982854	0.196585473				
0.157471	1.988033	0.197613667				
0.158471	1.990308	0.198066314				
0.158638	1.990687	0.198141805				
0.160548	1.995007	0.199002554				
0.161872	1.997981	0.199596321				
0.161955	1.998166	0.199633392				
0.162944	2.000376	0.200075246				
0.163438	2.001478	0.200295809				
0.165082	2.005126	0.201026611				
0.170625	2.017263	0.203467456				
0.173532	2.023527	0.204733153				
0.173854	2.024218	0.204872862				

Figure 51. Excel workbook: sheet 6, dataset for key metrics.

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Potential Results from use of Simulation Spreadsheet

Scenario	System Reliability	Reliability Effect	Total Data Variance	System Variance	Total Loss	
Scenario 1	99%	1	1295.9	1295.904154	$ 5.40	S I M U A L T I O N
Scenario 2	95%	1.2	1295.9	1555.084985	$ 5.92	
Scenario 3	90%	1.4	1295.9	1814.265816	$ 6.39	
Scenario 4	85%	1.6	1295.9	2073.446646	$ 6.83	
Scenario 5	80%	1.8	1295.9	2332.627477	$ 7.24	

Results	Metrics		LSL	USL	Target	Mean	Std. Dev.	Variance	k-Value	Loss/unit		Loss/Metric
	Chip Size	(cm)	20.1	-	18	24.43	18.55	344.20	0.05	$ 47.04		$ 47,043.31
	Moisture Content	(%)	10	21	10	14.88	2.35	5.50	0.1	$ 2.93		$ 2,934.01
	Ash Content	(%)	1.5	-	1.5	3.01	0.61	0.37	0.05	$ 0.47		$ 472.71
											Total Loss	$ 50,450.03

	Biomass		Flaker		Dryer		Milling		Blending		Densification
Reliability/Stage	P1		P2		P3		P4		P5		P6
(%)	99.56		99.04		93.30		93.12		95.50		96.73
Total Reliability	P1										
(%)	77%										

Figure 52. Excel workbook: sheet 7, summary results.

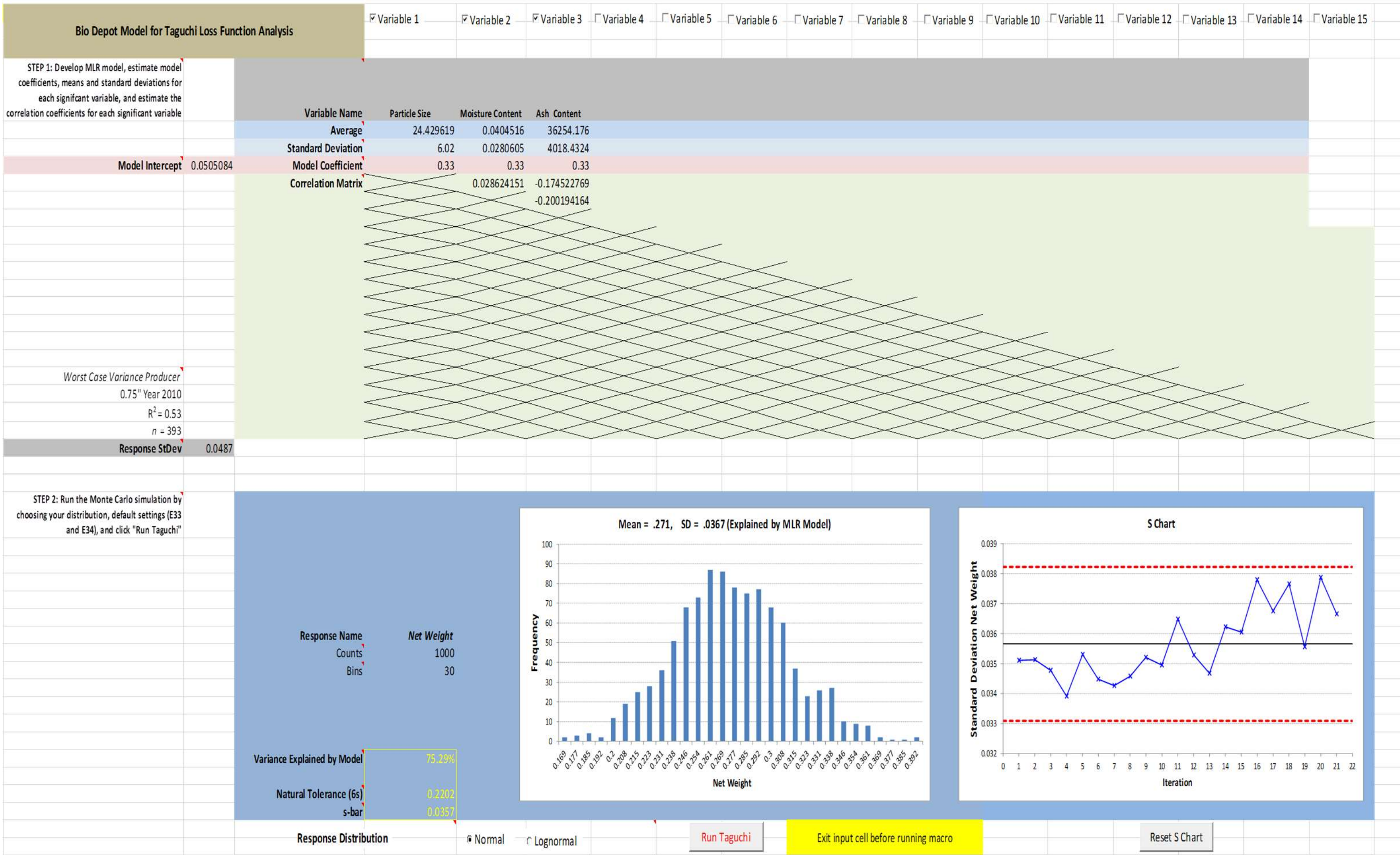

Figure 53. Excel workbook: sheet 6-1, bio-depot model for Taguchi Loss Function.

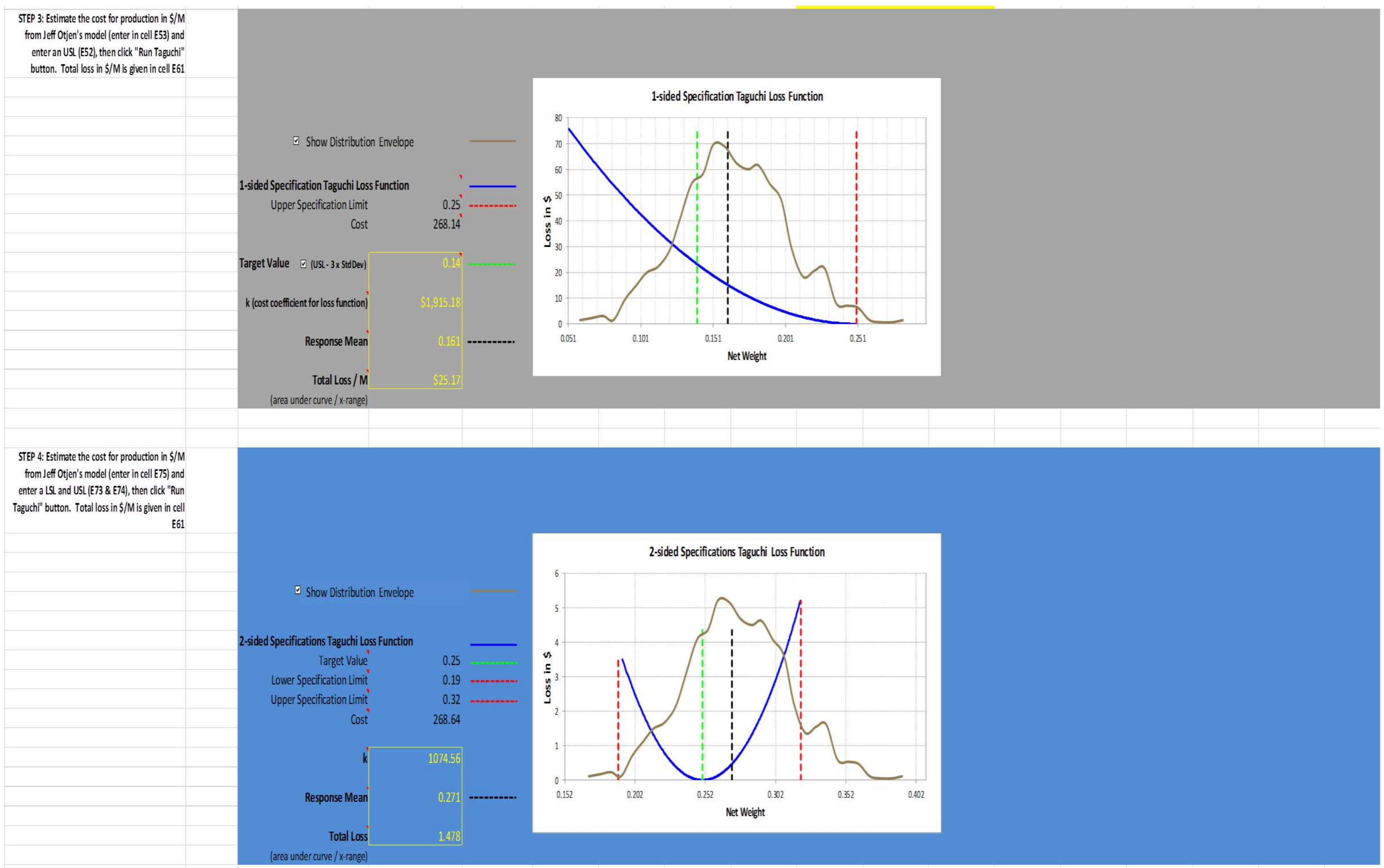

Figure 54. Excel workbook: sheet 6-2, bio-depot model for Taguchi Loss Function.

Virtual Basic Analysis_ Code for Reliability Block Diagram

```
Sub calc_formula()
Dim v1 As Double
Dim v2 As Double
Dim v3 As Double
Dim v4 As Double
Dim v5 As Double
Dim v6 As Double
Dim result1 As Double
Range("F8").Select
v1 = ActiveCell.Value
Range("F11").Select
v2 = ActiveCell.Value
Range("F14").Select
v3 = ActiveCell.Value
Range("F17").Select
v4 = ActiveCell.Value
Range("F20").Select
v5 = ActiveCell.Value
Range("F23").Select
v6 = ActiveCell.Value
Range("J25").Select
 ActiveCell.Value = v1 * v2 * v3 * v4 * v5 * v6
End Sub
```

Virtual Basic Analysis_ Code for Taguchi Loss Function, (Young *et al.*, 2014)

```
Dim CounterSbar As Integer
Dim Sbar() As Double
Dim x_Sbar() As Double
Dim IndivSDev As Double

Sub Taguchi()
'
' Taguchi Macro
Dim i As Integer
Dim j As Integer
'
'Response Calculations
Dim CleanInputs As Boolean
Dim VarExpl_y_val As Double
Dim VariableCount As Integer
Dim VarResp As Double
Dim MeanResp As Double
Dim RespRowCount As Integer
Dim RespBinCount As Integer
Dim y_val() As Double
Dim y_val_s() As Double
Dim RespBin() As Double
Dim RespBin_Label() As Double
Dim RespFreq()
RespRowCount = Worksheets("Taguchi").Range("$E$33").Value
RespBinCount = Worksheets("Taguchi").Range("$E$34").Value
ReDim RespBin(RespBinCount - 2)
ReDim RespBin_Label(RespBinCount - 1)
ReDim y_val(RespRowCount - 1)
ReDim y_val_s(RespRowCount - 1)
VariableCount = 0
Dim ChkBx As OLEObject
For i = 1 To 15
   If Worksheets("Taguchi").OLEObjects("ChkBx_Var" & CStr(i)).Object.Value =
True Then
      VariableCount = VariableCount + 1
   Else
      Exit For
   End If
Next i
```

```
''
'Read and Check Targets, LSL, and USL
CleanInputs = False
Dim TargetValue As Double
Dim TargetValue1 As Double
Dim LSL As Double
Dim USL As Double
Dim USL1 As Double
TargetValue = Worksheets("Taguchi").Range("$E$72").Value
LSL = Worksheets("Taguchi").Range("$E$73").Value
USL = Worksheets("Taguchi").Range("$E$74").Value
If TargetValue > LSL Then
   CleanInputs = True
   If TargetValue < USL Then
      CleanInputs = True
   Else
      CleanInputs = False
      MsgBox ("Please Enter an Upper Spec Limit Value Superior to Target
Value")
   End If
Else
   CleanInputs = False
   MsgBox ("Please Enter a Lower Spec Limit Value Inferior to Target Value")
End If
''
If CleanInputs = True Then
   MeanResp = Worksheets("Taguchi").Range("$C$7").Value
   For i = 1 To VariableCount
      MeanResp = MeanResp + Worksheets("Taguchi").Cells(5, 4 + i).Value *
Worksheets("Taguchi").Cells(7, 4 + i).Value
   Next i
   VarResp = 0
   For i = 1 To VariableCount
      VarResp = VarResp + Worksheets("Taguchi").Cells(6, 4 + i).Value ^ 2 *
Worksheets("Taguchi").Cells(7, 4 + i).Value ^ 2
   Next i
   For i = 1 To VariableCount - 1
      For j = i + 1 To VariableCount
         VarResp = VarResp + 2 * Worksheets("Taguchi").Cells(7, 4 + i).Value *
Worksheets("Taguchi").Cells(7, 4 + j).Value * Worksheets("Taguchi").Cells(7 +
i, 4 + j).Value * Worksheets("Taguchi").Cells(6, 4 + i).Value *
Worksheets("Taguchi").Cells(6, 4 + j).Value
```

```
        'MsgBox (Str(Worksheets("Taguchi").Cells(7, 4 + i).Value) + "," +
Str(Worksheets("Taguchi").Cells(7, 4 + j).Value) + "," +
Str(Worksheets("Taguchi").Cells(7 + i, 4 + j).Value) + "," +
Str(Worksheets("Taguchi").Cells(6, 4 + i).Value) + "," +
Str(Worksheets("Taguchi").Cells(6, 4 + j).Value))
      Next j
   Next i
   '
   If RB_Normal.Value = True Then
      For i = 0 To (RespRowCount - 1)
         y_val(i) = Excel.Application.WorksheetFunction.NormInv(Math.Rnd,
MeanResp, VarResp ^ 0.5)
         y_val_s(i) = y_val(i)
      Next i
   Else
      For i = 0 To (RespRowCount - 1)
         y_val(i) = Log(Excel.Application.WorksheetFunction.LogInv(Math.Rnd,
MeanResp, VarResp ^ 0.5))
         y_val_s(i) = y_val(i)
      Next i
   End If
   For i = 0 To (RespBinCount - 2)
      RespBin(i) = ((Excel.Application.WorksheetFunction.Max(y_val) -
Excel.Application.WorksheetFunction.Min(y_val)) / RespBinCount) * (i + 1) +
Excel.Application.WorksheetFunction.Min(y_val)
      RespBin_Label(i) = Math.Round(RespBin(i), 3)
   Next i
   RespBin_Label(i) =
Math.Round(((Excel.Application.WorksheetFunction.Max(y_val) -
Excel.Application.WorksheetFunction.Min(y_val)) / RespBinCount) * (i + 1) +
Excel.Application.WorksheetFunction.Min(y_val), 3)
   RespFreq = Excel.Application.WorksheetFunction.Frequency(y_val,
RespBin)
   ''
   ''
   'Taguchi Loss Function, 2-Sided
   Dim LossFunction() As Double
   Dim LossFunction_4chart() As Double
   Dim y_val_4chart() As Double
   Dim counter_y As Integer
   Dim k As Double
   counter_y = -1
```

```
k = Worksheets("Taguchi").Range("$E$75").Value / TargetValue
Worksheets("Taguchi").Range("$E$77").Value = Round(k, 3)
y_val_s = BubbleSrt(y_val_s, True)
ReDim LossFunction(RespRowCount - 1)
For i = 0 To RespRowCount - 1
   LossFunction(i) = k * (y_val_s(i) - TargetValue) ^ 2
   If y_val_s(i) > LSL Then
      If y_val_s(i) < USL Then
         counter_y = counter_y + 1
         If counter_y = 0 Then
            ReDim y_val_4chart(counter_y)
            ReDim LossFunction_4chart(counter_y)
         Else
            ReDim Preserve y_val_4chart(counter_y)
            ReDim Preserve LossFunction_4chart(counter_y)
         End If
         y_val_4chart(counter_y) = y_val_s(i)
         LossFunction_4chart(counter_y) = LossFunction(i)
      End If
   End If
Next i
''
'Prep Data for Taguchi Loss Function 1 sided chart
Dim x_vlineMean(1) As Double
Dim y_vlineMean(1) As Double
Dim x_vlineMean1(1) As Double
Dim y_vlineLSL(1) As Double
Dim y_vlineUSL(1) As Double
Dim x_vlineLSL(1) As Double
Dim x_vlineUSL(1) As Double
Dim x_vlineTarget(1) As Double
Dim x_vlineTarget1(1) As Double
Dim y_vline1(1) As Double
Dim x_vlineUSL1(1) As Double
Dim y_val1() As Double
Dim LossFunction1() As Double
Dim k1 As Double
y_vlineLSL(0) = 0
y_vlineLSL(1) = LossFunction_4chart(0)
y_vlineUSL(0) = 0
y_vlineUSL(1) = LossFunction_4chart(UBound(LossFunction_4chart))
x_vlineLSL(0) = LSL
```

```
    x_vlineLSL(1) = LSL
    x_vlineUSL(0) = USL
    x_vlineUSL(1) = USL
    'Area under the curve calculation 2-sided TLF
    Dim Area As Double
    Area = 0
    For i = 0 To UBound(LossFunction) - 1
        If y_val_s(i) > LSL Then
            If y_val_s(i + 1) < USL Then
                Area = Area + ((LossFunction(i) + LossFunction(i + 1)) / 2) * (y_val_s(i
+ 1) - y_val_s(i))
            Else
                Exit For
            End If
        End If
    Next i
    Area = Area / (y_val_4chart(UBound(y_val_4chart)) - y_val_4chart(0))
    Dim MeanResp1 As Double
    MeanResp1 = Excel.Application.WorksheetFunction.Average(y_val)
    Worksheets("Taguchi").Range("$E$79").Value =
Str(Math.Round(MeanResp1, 3))
    Worksheets("Taguchi").Range("$E$41").Value =
Math.Round(Excel.Application.WorksheetFunction.StDev(y_val), 4) * 6
    x_vlineMean(0) = Worksheets("Taguchi").Range("$E$79").Value
    x_vlineMean(1) = x_vlineMean(0)
    y_vlineMean(0) = 0
    y_vlineMean(1) = (y_vlineLSL(1) + y_vlineUSL(1)) / 2
    Worksheets("Taguchi").Range("$E$81").Value = Round(Area, 3)
    x_vlineTarget(0) = Worksheets("Taguchi").Range("$E$72").Value
    x_vlineTarget(1) = x_vlineTarget(0)
    Worksheets("Taguchi").Range("$E$39").Value =
Excel.Application.WorksheetFunction.StDev(y_val) /
Worksheets("Taguchi").Range("$C$23").Value
    IndivSDev = Excel.Application.WorksheetFunction.StDev(y_val)
    CounterSbar = CounterSbar + 1
    ''
    Dim objChrt_Resp As ChartObject
    Dim chrt_Resp As Chart
    Dim s_Resp As Series
    Set objChrt_Resp = Worksheets("Taguchi").ChartObjects("Chart Resp")
    Set chrt_Resp = objChrt_Resp.Chart
    chrt_Resp.ChartType = xlColumnClustered
```

```
    Set s_Resp = chrt_Resp.SeriesCollection(1)
    s_Resp.XValues = RespBin_Label
    s_Resp.Values = RespFreq
    chrt_Resp.Axes(xlCategory, xlPrimary).HasTitle = True
    chrt_Resp.Axes(xlCategory, xlPrimary).AxisTitle.Font.Size = 12
    chrt_Resp.Axes(xlValue, xlPrimary).AxisTitle.Font.Size = 14
    chrt_Resp.Axes(xlCategory,        xlPrimary).AxisTitle.Characters.Text        =
Worksheets("Taguchi").Range("$E$32").Value
    chrt_Resp.Axes(xlValue, xlPrimary).HasTitle = True
    chrt_Resp.Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Frequency"
    chrt_Resp.HasTitle = True
    chrt_Resp.ChartTitle.Text          =          "Mean          =          "          +
Str(Worksheets("Taguchi").Range("$E$79").Value)   +   ",          SD   =   "   +
Str(Math.Round(IndivSDev, 4)) + " (Explained by MLR Model)"
    chrt_Resp.ChartTitle.Font.Size = 14
    '
    Dim objChrt_Tag As ChartObject
    Dim chrt_Tag As Chart
    Dim s_Tag As Series
    Set objChrt_Tag = Worksheets("Taguchi").ChartObjects("Taguchi 2")
    Set chrt_Tag = objChrt_Tag.Chart
    chrt_Tag.SeriesCollection(6).Delete
    chrt_Tag.ChartType = xlXYScatterLinesNoMarkers
    Set s_Tag = chrt_Tag.SeriesCollection(1)
    s_Tag.XValues = y_val_4chart
    s_Tag.Values = LossFunction_4chart
    s_Tag.MarkerSize = 5
    s_Tag.Border.Color = RGB(0, 0, 255)
    s_Tag.Format.Line.DashStyle = msoLineSolid
    s_Tag.AxisGroup = xlPrimary
    chrt_Tag.Axes(xlCategory, xlPrimary).HasTitle = True
    chrt_Tag.Axes(xlCategory,        xlPrimary).AxisTitle.Characters.Text        =
Worksheets("Taguchi").Range("$E$32").Value
    chrt_Tag.Axes(xlCategory, xlPrimary).AxisTitle.Font.Size = 12
    chrt_Tag.Axes(xlValue, xlPrimary).HasTitle = True
    chrt_Tag.Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Loss in $"
    chrt_Tag.Axes(xlValue, xlPrimary).AxisTitle.Font.Size = 14
    chrt_Tag.Axes(xlCategory,              xlPrimary).MinimumScale              =
Round(Excel.Application.WorksheetFunction.Min(RespBin_Label(0)   -   0.1   *
RespBin_Label(0), LSL - 0.1 * LSL, TargetValue - 0.1 * TargetValue), 3)
    chrt_Tag.Axes(xlCategory,              xlPrimary).MaximumScale              =
Round(Excel.Application.WorksheetFunction.Max(RespBin_Label(UBound(Re
```

```
spBin_Label)) + 0.1 * RespBin_Label(0), USL + 0.1 * RespBin_Label(0),
TargetValue + 0.1 * RespBin_Label(0)), 3)
    chrt_Tag.Axes(xlCategory, xlPrimary).MajorUnitIsAuto = True
    chrt_Tag.HasTitle = True
    chrt_Tag.ChartTitle.Text = Worksheets("Taguchi").Range("$D$71").Value
    chrt_Tag.ChartTitle.Font.Size = 14
    '
    Dim s_TagLSL As Series
    Set s_TagLSL = chrt_Tag.SeriesCollection(2)
    s_TagLSL.XValues = x_vlineLSL
    s_TagLSL.AxisGroup = xlPrimary
    s_TagLSL.Values = y_vlineLSL
    s_TagLSL.Border.Color = RGB(255, 0, 0)
    s_TagLSL.Format.Line.DashStyle = msoLineSysDash
    '
    Dim s_TagUSL As Series
    Set s_TagUSL = chrt_Tag.SeriesCollection(3)
    s_TagUSL.XValues = x_vlineUSL
    s_TagUSL.AxisGroup = xlPrimary
    s_TagUSL.Values = y_vlineUSL
    s_TagUSL.Border.Color = RGB(255, 0, 0)
    s_TagUSL.Format.Line.DashStyle = msoLineSysDash
    '
    Dim s_TagMean As Series
    Set s_TagMean = chrt_Tag.SeriesCollection(4)
    s_TagMean.XValues = x_vlineMean
    s_TagMean.AxisGroup = xlPrimary
    s_TagMean.Values = y_vlineMean
    s_TagMean.Border.Color = RGB(0, 0, 0)
    s_TagMean.Format.Line.DashStyle = msoLineSysDash
    '
    Dim s_TagTarget As Series
    Set s_TagTarget = chrt_Tag.SeriesCollection(5)
    s_TagTarget.XValues = x_vlineTarget
    s_TagTarget.AxisGroup = xlPrimary
    s_TagTarget.Values = y_vlineMean
    s_TagTarget.Border.Color = RGB(0, 255, 0)
    s_TagTarget.Format.Line.DashStyle = msoLineSysDash
    '
    chrt_Tag.SeriesCollection.NewSeries
    Dim s_Distri As Series
    Set s_Distri = chrt_Tag.SeriesCollection(6)
```

```
    s_Distri.AxisGroup = xlSecondary
    s_Distri.XValues = RespBin_Label
    s_Distri.Values = RespFreq
    s_Distri.Border.Color = RGB(148, 128, 84)
    s_Distri.ChartType = xlXYScatterSmoothNoMarkers
    Call ChBx_ShowDistri_Click
    chrt_Tag.Axes(xlValue, xlSecondary).MajorTickMark = xlNone
    chrt_Tag.Axes(xlValue, xlSecondary).TickLabelPosition = xlNone
    ''
    ''
    'One sided loss function calculation
    Dim S3 As Double
    S3 = Excel.Application.WorksheetFunction.StDev(y_val) * 3
    USL1 = Worksheets("Taguchi").Range("$E$52").Value
    If Worksheets("Taguchi").DrawingObjects("ChBx_3S").Value = 1 Then
        TargetValue1 = USL1 - S3
        Worksheets("Taguchi").Range("$E$55").Font.Color = RGB(255, 255, 0)
    Else
        TargetValue1 = Worksheets("Taguchi").Range("$E$55").Value
        Worksheets("Taguchi").Range("$E$55").Font.Color = RGB(0, 0, 0)
    End If
    If TargetValue1 > 0 Then
        If USL1 < y_val_s(UBound(y_val_s)) Then
            Dim counterTLF1 As Integer
            counterTLF1 = -1
            k1 = Worksheets("Taguchi").Range("$E$53").Value / TargetValue1
            Worksheets("Taguchi").Range("$E$57").Value = Round(k1, 3)
            If Worksheets("Taguchi").DrawingObjects("ChBx_3S").Value = 1 Then
                MeanResp1 = MeanResp1 - S3
                Worksheets("Taguchi").Range("$E$55").Value                  =
Round(TargetValue1, 3)
                For i = 0 To UBound(y_val_s)
                    counterTLF1 = counterTLF1 + 1
                    If counterTLF1 = 0 Then
                        ReDim LossFunction1(counterTLF1)
                        ReDim y_val1(counterTLF1)
                    Else
                        ReDim Preserve LossFunction1(counterTLF1)
                        ReDim Preserve y_val1(counterTLF1)
                    End If
                    LossFunction1(counterTLF1) = k1 * ((y_val_s(i) - S3) - USL1) ^ 2
                    y_val1(counterTLF1) = y_val_s(i) - S3
```

```
            If ((y_val_s(i) - S3) - USL1) > 0 Then
                LossFunction1(counterTLF1) = 0
                y_val1(counterTLF1) = USL1
                Exit For
            End If
        Next i
    Else
        For i = 0 To UBound(y_val_s)
            counterTLF1 = counterTLF1 + 1
            If counterTLF1 = 0 Then
                ReDim LossFunction1(counterTLF1)
                ReDim y_val1(counterTLF1)
            Else
                ReDim Preserve LossFunction1(counterTLF1)
                ReDim Preserve y_val1(counterTLF1)
            End If
            LossFunction1(counterTLF1) = k1 * (y_val_s(i) - USL1) ^ 2
            y_val1(counterTLF1) = y_val_s(i)
            If (y_val_s(i) - USL1) > 0 Then
                LossFunction1(counterTLF1) = 0
                y_val1(counterTLF1) = USL1
                Exit For
            End If
        Next i
    End If
''
'Area under the curve calculation one-sided TLF
Dim Area1 As Double
Area1 = 0
For i = 0 To UBound(LossFunction1) - 1
    Area1 = Area1 + ((LossFunction1(i) + LossFunction1(i + 1)) / 2) *
(y_val1(i + 1) - y_val1(i))
Next i
Area1 = Area1 / (y_val1(UBound(y_val1)) - y_val1(0))
Worksheets("Taguchi").Range("$E$59").Value =
Str(Math.Round(MeanResp1, 3))
Worksheets("Taguchi").Range("$E$61").Value = Round(Area1, 3)
x_vlineMean1(0) = Worksheets("Taguchi").Range("$E$59").Value
x_vlineMean1(1) = x_vlineMean1(0)
x_vlineTarget1(0) = TargetValue1
x_vlineTarget1(1) = x_vlineTarget1(0)
x_vlineUSL1(0) = USL1
```

```
x_vlineUSL1(1) = x_vlineUSL1(0)
y_vline1(0) = 0
y_vline1(1) = LossFunction1(0)
Dim RespBin_Label_Shifted()
ReDim RespBin_Label_Shifted(UBound(RespBin_Label))
If Worksheets("Taguchi").DrawingObjects("ChBx_3S").Value = 1 Then
   For i = 0 To UBound(RespBin_Label_Shifted)
      RespBin_Label_Shifted(i) = RespBin_Label(i) - S3
   Next i
End If
''
Dim objChrt_Tag1 As ChartObject
Dim chrt_Tag1 As Chart
Dim s_Tag1 As Series
Dim s_TagUSL1 As Series
Set objChrt_Tag1 = Worksheets("Taguchi").ChartObjects("Taguchi 1")
Set chrt_Tag1 = objChrt_Tag1.Chart
chrt_Tag1.SeriesCollection(5).Delete
chrt_Tag1.ChartType = xlXYScatterLinesNoMarkers
Set s_Tag1 = chrt_Tag1.SeriesCollection(1)
s_Tag1.AxisGroup = xlPrimary
s_Tag1.XValues = y_val1
s_Tag1.Values = LossFunction1
s_Tag1.Border.Color = RGB(0, 0, 255)
chrt_Tag1.Axes(xlCategory, xlPrimary).HasTitle = True
chrt_Tag1.Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text =
Worksheets("Taguchi").Range("$E$32").Value
chrt_Tag1.Axes(xlCategory, xlPrimary).AxisTitle.Font.Size = 12
chrt_Tag1.Axes(xlValue, xlPrimary).HasTitle = True
chrt_Tag1.Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Loss in $"
chrt_Tag1.Axes(xlValue, xlPrimary).AxisTitle.Font.Size = 14
chrt_Tag1.Axes(xlCategory, xlPrimary).MinimumScale = Round(y_val1(0),
3)
chrt_Tag1.Axes(xlCategory, xlPrimary).MaximumScale =
Round(Excel.Application.WorksheetFunction.Max(RespBin_Label_Shifted(UBo
und(RespBin_Label_Shifted)) + 0.1 * y_val_s(0), y_val1(UBound(y_val1)) + 0.1
* y_val_s(0), USL1 + 0.1 * y_val_s(0)), 3)
chrt_Tag1.Axes(xlCategory, xlPrimary).MajorUnitIsAuto = True
chrt_Tag1.HasTitle = True
chrt_Tag1.ChartTitle.Text =
Worksheets("Taguchi").Range("$D$51").Value
chrt_Tag1.ChartTitle.Font.Size = 14
```

```
    '
    Set s_TagUSL1 = chrt_Tag1.SeriesCollection(2)
    s_TagUSL1.XValues = x_vlineUSL1
    s_TagUSL1.AxisGroup = xlPrimary
    s_TagUSL1.Values = y_vline1
    s_TagUSL1.Border.Color = RGB(255, 0, 0)
    s_TagUSL1.Format.Line.DashStyle = msoLineSysDash
    '
    Dim s_TagMean1 As Series
    Set s_TagMean1 = chrt_Tag1.SeriesCollection(3)
    s_TagMean1.XValues = x_vlineMean1
    s_TagMean1.AxisGroup = xlPrimary
    s_TagMean1.Values = y_vline1
    s_TagMean1.Border.Color = RGB(0, 0, 0)
    s_TagMean1.Format.Line.DashStyle = msoLineSysDash
    '
    Dim s_TagTarget1 As Series
    Set s_TagTarget1 = chrt_Tag1.SeriesCollection(4)
    s_TagTarget1.XValues = x_vlineTarget1
    s_TagTarget1.AxisGroup = xlPrimary
    s_TagTarget1.Values = y_vline1
    s_TagTarget1.Border.Color = RGB(0, 255, 0)
    s_TagTarget1.Format.Line.DashStyle = msoLineSysDash
    '
    chrt_Tag1.SeriesCollection.NewSeries
    Dim s_Distri2 As Series
    Set s_Distri2 = chrt_Tag1.SeriesCollection(5)
    If Worksheets("Taguchi").DrawingObjects("ChBx_3S").Value = 1 Then
        s_Distri2.XValues = RespBin_Label_Shifted
    Else
        s_Distri2.XValues = RespBin_Label
    End If
    s_Distri2.AxisGroup = xlSecondary
    s_Distri2.Values = RespFreq
    s_Distri2.Border.Color = RGB(148, 128, 84)
    s_Distri2.ChartType = xlXYScatterSmoothNoMarkers
    chrt_Tag1.Axes(xlValue, xlSecondary).MajorTickMark = xlNone
    chrt_Tag1.Axes(xlValue, xlSecondary).TickLabelPosition = xlNone
    ''
    Call SBarChart
Else
```

```
      MsgBox ("Target Value for one-sided Taguchi Loss Function is Too High," & vbCrLf & "Please Enter a Smaller Value")
   End If
   Else
      MsgBox ("Upper Specification Limit is Too Small Compared to the Response Standard Deviation")
   End If
End If
End Sub

Sub SBarChart()
   Dim AvMovRange As Double
   Dim AvSbar As Double
   Dim i As Integer
   Dim x_sLSL(1) As Double
   Dim y_sLSL(1) As Double
   Dim y_sUSL(1) As Double
   Dim y_sCL(1) As Double
   AvMovRange = 0
   If CounterSbar = 1 Then
      ReDim Sbar(0)
      Sbar(0) = IndivSDev
      ReDim x_Sbar(0)
      x_Sbar(0) = CounterSbar
   ElseIf CounterSbar > 1 Then
      ReDim Preserve Sbar(CounterSbar - 1)
      Sbar(CounterSbar - 1) = IndivSDev
      ReDim Preserve x_Sbar(CounterSbar - 1)
      x_Sbar(CounterSbar - 1) = CounterSbar
      For i = 1 To UBound(Sbar)
         AvMovRange = AvMovRange + Abs(Sbar(i) - Sbar(i - 1))
      Next i
      AvMovRange = AvMovRange / UBound(Sbar)
      AvSbar = Excel.Application.WorksheetFunction.Average(Sbar)
      ''
      x_sLSL(0) = 0
      x_sLSL(1) = CounterSbar + 1
      y_sLSL(0) = AvSbar - 2.66 * AvMovRange
      y_sLSL(1) = y_sLSL(0)
      y_sUSL(0) = AvSbar + 2.66 * AvMovRange
      y_sUSL(1) = y_sUSL(0)
      y_sCL(0) = AvSbar
```

```
    y_sCL(1) = y_sCL(0)
    '
    Worksheets("Taguchi").Range("$E$42").Value = Round(AvSbar, 4)
    ''
    'Populate Sbar Chart
    Dim objChrt_Sbar As ChartObject
    Dim chrt_Sbar As Chart
    Set objChrt_Sbar = Worksheets("Taguchi").ChartObjects("Chart sbar")
    Set chrt_Sbar = objChrt_Sbar.Chart
    'chrt_Tag1.SeriesCollection(5).Delete
    chrt_Sbar.ChartType = xlXYScatterLinesNoMarkers
    chrt_Sbar.Axes(xlCategory, xlPrimary).HasTitle = True
    chrt_Sbar.Axes(xlCategory,       xlPrimary).AxisTitle.Characters.Text       =
"Iteration"
    chrt_Sbar.Axes(xlCategory, xlPrimary).AxisTitle.Font.Size = 12
    chrt_Sbar.Axes(xlValue, xlPrimary).HasTitle = True
    chrt_Sbar.Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Standard
Deviation " + Worksheets("Taguchi").Range("$E$32").Value
    chrt_Sbar.Axes(xlValue, xlPrimary).AxisTitle.Font.Size = 14
    chrt_Sbar.Axes(xlCategory, xlPrimary).MinimumScale = 0
    chrt_Sbar.Axes(xlCategory, xlPrimary).MaximumScale = CounterSbar + 1
    chrt_Sbar.Axes(xlCategory, xlPrimary).MajorUnitIsAuto = False
    chrt_Sbar.Axes(xlCategory, xlPrimary).MajorUnit = 1
    chrt_Sbar.HasTitle = True
    chrt_Sbar.ChartTitle.Text = "S Chart"
    chrt_Sbar.ChartTitle.Font.Size = 14
    '
    Dim sLSL As Series
    Set sLSL = chrt_Sbar.SeriesCollection(1)
    sLSL.AxisGroup = xlPrimary
    sLSL.XValues = x_sLSL
    sLSL.Values = y_sLSL
    sLSL.Border.Color = RGB(255, 0, 0)
    sLSL.Format.Line.DashStyle = msoLineSysDash
    '
    Dim sUSL As Series
    Set sUSL = chrt_Sbar.SeriesCollection(2)
    sUSL.AxisGroup = xlPrimary
    sUSL.XValues = x_sLSL
    sUSL.Values = y_sUSL
    sUSL.Border.Color = RGB(255, 0, 0)
    sUSL.Format.Line.DashStyle = msoLineSysDash
```

```
        '
        Dim sCL As Series
        Set sCL = chrt_Sbar.SeriesCollection(3)
        sCL.AxisGroup = xlPrimary
        sCL.XValues = x_sLSL
        sCL.Values = y_sCL
        sCL.Border.Color = RGB(0, 0, 0)
        sCL.Format.Line.DashStyle = msoLineSolid
        sCL.Format.Line.Weight = 1.25
        '
        Dim xy_sBar As Series
        Set xy_sBar = chrt_Sbar.SeriesCollection(4)
        xy_sBar.ChartType = xlXYScatterLines
        xy_sBar.AxisGroup = xlPrimary
        xy_sBar.XValues = x_Sbar
        xy_sBar.Values = Sbar
        xy_sBar.MarkerStyle = xlMarkerStyleX
        xy_sBar.MarkerSize = 5
        xy_sBar.MarkerForegroundColor = RGB(0, 0, 255)
        xy_sBar.Border.Color = RGB(0, 0, 255)
        xy_sBar.Format.Line.Weight = 1.25
        xy_sBar.Format.Line.DashStyle = msoLineSolid
    End If
End Sub

Sub ChBx_ShowDistri_Click()
    Dim objChrt_Tag As ChartObject
    Dim chrt_Tag As Chart
    Set objChrt_Tag = Worksheets("Taguchi").ChartObjects("Taguchi 2")
    Set chrt_Tag = objChrt_Tag.Chart
    Dim s_Distri As Series
    Set s_Distri = chrt_Tag.SeriesCollection(6)
    If  Worksheets("Taguchi").DrawingObjects("ChBx_ShowDistri").Value  =  1
Then
        s_Distri.Format.Line.Visible = msoTrue
        s_Distri.Border.Color = RGB(148, 128, 84)
    Else
        s_Distri.Format.Line.Visible = msoFalse
    End If
End Sub

Sub ChBx_ShowDistri2_Click()
```

```
    Dim objChrt_Tag1 As ChartObject
    Dim chrt_Tag1 As Chart
    Set objChrt_Tag1 = Worksheets("Taguchi").ChartObjects("Taguchi 1")
    Set chrt_Tag1 = objChrt_Tag1.Chart
    Dim s_Distri2 As Series
    Set s_Distri2 = chrt_Tag1.SeriesCollection(5)
    If  Worksheets("Taguchi").DrawingObjects("ChBx_ShowDistri2").Value  =  1
Then
        s_Distri2.Format.Line.Visible = msoTrue
        s_Distri2.Border.Color = RGB(148, 128, 84)
    Else
        s_Distri2.Format.Line.Visible = msoFalse
    End If
End Sub


Private Sub ChkBx_Var1_Click()
    If ChkBx_Var1.Value = False Then
        ChkBx_Var1.Value = True
    End If
End Sub

Private Sub ChkBx_Var2_Click()
    If ChkBx_Var2.Value = False Then
        ChkBx_Var2.Value = True
    End If
End Sub

Private Sub ChkBx_Var3_Click()
    If ChkBx_Var2.Value = True Then
        If ChkBx_Var4.Value = True Then
            ChkBx_Var3.Value = True
        End If
    Else
        ChkBx_Var3.Value = False
    End If
End Sub

Private Sub ChkBx_Var4_Click()
    If ChkBx_Var3.Value = True Then
        If ChkBx_Var5.Value = True Then
            ChkBx_Var4.Value = True
```

```
      End If
   Else
      ChkBx_Var4.Value = False
   End If
End Sub

Private Sub ChkBx_Var5_Click()
   If ChkBx_Var4.Value = True Then
      If ChkBx_Var6.Value = True Then
         ChkBx_Var5.Value = True
      End If
   Else
      ChkBx_Var5.Value = False
   End If
End Sub

Private Sub ChkBx_Var6_Click()
   If ChkBx_Var5.Value = True Then
      If ChkBx_Var7.Value = True Then
         ChkBx_Var6.Value = True
      End If
   Else
      ChkBx_Var6.Value = False
   End If
End Sub

Private Sub ChkBx_Var7_Click()
   If ChkBx_Var6.Value = True Then
      If ChkBx_Var8.Value = True Then
         ChkBx_Var7.Value = True
      End If
   Else
      ChkBx_Var7.Value = False
   End If
End Sub

Private Sub ChkBx_Var8_Click()
   If ChkBx_Var7.Value = True Then
      If ChkBx_Var9.Value = True Then
         ChkBx_Var8.Value = True
      End If
   Else
```

```
      ChkBx_Var8.Value = False
   End If
End Sub

Private Sub ChkBx_Var9_Click()
   If ChkBx_Var8.Value = True Then
      If ChkBx_Var10.Value = True Then
         ChkBx_Var9.Value = True
      End If
   Else
      ChkBx_Var9.Value = False
   End If
End Sub


Private Sub ChkBx_Var10_Click()
   If ChkBx_Var9.Value = True Then
      If ChkBx_Var11.Value = True Then
         ChkBx_Var10.Value = True
      End If
   Else
      ChkBx_Var10.Value = False
   End If
End Sub

Private Sub ChkBx_Var11_Click()
   If ChkBx_Var10.Value = True Then
      If ChkBx_Var12.Value = True Then
         ChkBx_Var11.Value = True
      End If
   Else
      ChkBx_Var11.Value = False
   End If
End Sub

Private Sub ChkBx_Var12_Click()
   If ChkBx_Var11.Value = True Then
      If ChkBx_Var13.Value = True Then
         ChkBx_Var12.Value = True
      End If
   Else
      ChkBx_Var12.Value = False
```

```
    End If
End Sub

Private Sub ChkBx_Var13_Click()
    If ChkBx_Var12.Value = True Then
        If ChkBx_Var14.Value = True Then
            ChkBx_Var13.Value = True
        End If
    Else
        ChkBx_Var13.Value = False
    End If
End Sub

Private Sub ChkBx_Var14_Click()
    If ChkBx_Var13.Value = True Then
        If ChkBx_Var15.Value = True Then
            ChkBx_Var14.Value = True
        End If
    Else
        ChkBx_Var14.Value = False
    End If
End Sub

Private Sub ChkBx_Var15_Click()
    If ChkBx_Var14.Value = True Then
        If ChkBx_Var15.Value = True Then
            ChkBx_Var15.Value = True
        Else
            ChkBx_Var15.Value = False
        End If
    Else
        ChkBx_Var15.Value = False
    End If
End Sub

Private Sub Cmd_Reset_Sbar_Click()
    CounterSbar = 0
    ReDim Sbar(0)
    ReDim x_Sbar(0)
End Sub

Private Sub Cmd_RunTaguchi_Click()
```

```
    Call Taguchi
End Sub

Public Function BubbleSrt(ArrayIn, Ascending As Boolean)

Dim SrtTemp As Variant
Dim i As Long
Dim j As Long


If Ascending = True Then
    For i = LBound(ArrayIn) To UBound(ArrayIn)
        For j = i + 1 To UBound(ArrayIn)
            If ArrayIn(i) > ArrayIn(j) Then
                SrtTemp = ArrayIn(j)
                ArrayIn(j) = ArrayIn(i)
                ArrayIn(i) = SrtTemp
            End If
        Next j
     Next i
Else
    For i = LBound(ArrayIn) To UBound(ArrayIn)
        For j = i + 1 To UBound(ArrayIn)
            If ArrayIn(i) < ArrayIn(j) Then
                SrtTemp = ArrayIn(j)
                ArrayIn(j) = ArrayIn(i)
                ArrayIn(i) = SrtTemp
            End If
        Next j
     Next i
End If

BubbleSrt = ArrayIn

End Function
```

VITA

Maximilian Platzer is from Vienna, Austria, where he accomplished his A-levels and an apprenticeship to a joiner. He attended the University of Applied Sciences in Salzburg, Austria, where he earned a B.S. in forest product technology.

During his undergraduate program, Max dealt with the “Study of heat transfer and gluing quality of three-layer solid wood panels with MUF adhesive”. Prior to the graduate program at UT he worked for the Norwegian company Green Resources, Africa’s largest forestation company, the leader in East African wood manufacturing. Due to his effort in Tanzania he was able to establish a collaboration between Green Resources and the University of Applied Sciences, Salzburg. He is currently Studying under Dr. Timothy Young at the Center for Renewable Carbon and his M.S. research focuses on variation within a merchandising depot for biomass.

He plans to graduate from the University of Tennessee with a “Master of Science degree in Wood Science Technology and Biomaterials” in August 2016.