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Design of a Process Control System for Combustion Regulation by Moisture Content Measurement in Biomass Feed

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Abstract

Biomass has the capacity to generate a major part of the global renewable energy demands due to its large supply, versatility, and readily exploitable nature. Biomass can be produced from natural sources like wood waste, grasses, trees, and fast-growing energy crops. Biomass wood chips are produced from crushed trees and can be fed into combustion systems to supply heat energy to buildings. However, depending on the type of trees, season of harvest and storage conditions of biomass wood chips the moisture content in the biomass wood chips may vary. The variation in moisture content of biomass wood chips is a major quality issue for large district heating systems because it has negative impacts on the overall system efficiency and heat exchange effectiveness. Notwithstanding, just a few research works have been done in this field. This research fills the knowledge gap by providing an overview of biomass combustion systems and moisture measuring techniques that are available in literature. It further builds on the existing literature by using SIPOC (suppliers, inputs, process, outputs, customers) process map and proportional-integral-derivative (PID) control loop to discuss the effects of varying moisture content on the biomass combustion system. The research presents the design of a process control system for combustion regulation using the measured moisture percentage in the biomass wood chips. The control system was designed using Lean Six Sigma tools and the seven major building blocks of the control system design process. The microwave moisture sensor was selected as the most suitable sensor for the process control and technical solutions for its installation were discussed. Experiments were also performed for process control and improvement, and they provide a basis for future research.

Keywords: Biomass, Heating System, Biomass Combustion System, SIPOC, PID Controller, Moisture Measurement, Lean Six Sigma.

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1 Introduction

Bioenergy is generated from biomass that can be transformed to solid, liquid, and gaseous biofuels which is eventually used for production of heat, power, and fuel for transportation. Bioenergy currently supplies more energy than what wind, hydro, solar and geothermal renewable energy sources can provide altogether [1]. According to Eurostat, the statistical office of the European Union, 62% of energy used by households in the European Union in 2020 was for heating their homes [2]. Therefore, the use of biomass as fuel for heating systems in buildings would be pivotal in solving global energy demands because building heating consumes great amounts of energy [3]. While biomass will be useful in solving global energy challenges, certain important criteria should be considered before selecting biomass as fuel for heating systems. Criteria such as initial investment cost, reliability, durability, and operating costs. The operating cost is influenced by the fuel cost and the overall efficiency of the system, and these two variables are the main economic factors used in selecting heating systems [3].

Biomass wood chips are prepared from crushed trees like pine, spruce or birch and contain very high water content. If biomass wood chips are available in large supply and meet the functional requirements of the heating system, it is also important that the operating cost is reduced to satisfactory limits through improvement in the overall efficiency of the system [3]. The water content in the wood chips depend on the type of trees, the season of harvest of the trees and the storage process of the biomass wood chips. The water content in the wood chips reduces the efficiency and the net heat released during the combustion process because drying and preheating of the wood chips needs to occur first in the combustion chamber [4, 5]. The moisture content in the biomass wood chips is typically reduced by natural drying. The rate of natural drying depends on the method of storage, storage period, temperature, and original moisture content of the biomass. Natural drying of biomass from a moisture content of about 50% to 30% takes almost six months. Another year is required to further reduce the moisture content to 15% and during this period microbial activities consumes a significant part of the biomass [4]. Forced drying of biomass wood chips can also be performed using heat dryers to further reduce the moisture content in the biomass but this can lead to loss of volatile matter in the wood chips [4]. Usually, when biomass wood chips are used in district heating systems or for industrial purposes, they are stored in large heaps to distribute the moisture away from the internal part of the heap to the external surface where the moisture can evaporate. However, studies show that even after 3 months of storage there is still a varying amount of moisture content throughout the heap [6, 7]. In periods of higher demand for heat energy and warming of buildings during the winter, biomass wood chips may not be stored for long periods, depending on the storage area available and the nature of the supply chain [6]. In any case, research reveals that it is currently infeasible to have low and constant moisture content in biomass wood chips that are used for large district heating systems and this is a cause of variation in the combustion performance and overall efficiency of the system [4, 6, 7]. In addition, even if the heap of biomass wood chips could be torrefied or dried to low moisture content levels using any of the recent drying technologies, then the temperatures of the hot gases released from the combustion process will increase but the heat exchange performance in the boiler would be low, consequently reducing the overall system efficiency [4, 8]. Therefore, this research seeks to design a process control system that can measure the moisture content in biomass wood chips. This process control system uses the measured moisture content as a control parameter in the regulation of other factors in the combustion process such as the air supply rate and the wood chips feed speed, thereby increasing the overall efficiency of the combustion process and the effective heat exchange.

1.1 Background

Dragefossen is a power company established in 1928 to provide electricity for locals in the Saltdal municipality in the Nordland county, Norway. Dragefossen currently has two power plants that both produce approximately 17 GWh per year and Dragefossen has gradually expanded its power line networks over the years through development and mergers. Dragefossen also has subsidiaries like Rognan Bioenergy and Fauske District Heating which supply heat to large buildings in their locality, using virgin wood chips from Pine, Spruce, and Birch trees as the energy source [9]. Fauske District Heating uses the KSM Multistoker XXL manufactured by KSM Stoker Denmark as the heating system for providing heating to buildings in the area. Figure 1 shows the KSM Multistoker XXL used in Fauske District Heating to supply heat to buildings [10].

Figure 1. KSM Multistoker XXL

1.2 Problem Description

A lot of research has been performed on the subject of improving biomass combustion performance in heating systems [11]. Biomass combustion systems which lower harmful emissions through the use of innovative air supply and exhaust gas treatment have been presented [12]. The design of a process control system for biomass-fired boilers by carbon monoxide emission measurement has been discussed [13]. An automatic control for feeding of biomass into the biomass combustion system based on the oxygen content of the combustion flue gases has also been experimented and investigated [14]. However, there is still a lack of information regarding the relationship between the moisture content in biomass wood chips and the overall efficiency of the biomass combustion systems [14]. The variability in the moisture content of biomass wood chips is a quality issue that is mostly disregarded in research, yet it can have negative consequences on the overall efficiency of biomass combustion systems and the effective heat exchange in heat exchangers [13, 14]. Therefore, the aim of this research is to design a process control system for combustion regulation of the KSM Multistoker XXL based on the measured value of moisture content in the biomass wood chips so that the overall efficiency of the biomass combustion system and the effective heat exchange can be optimized.

1.3 Research Objectives

The research seeks to address the inefficiencies associated with the KSM Multistoker XXL due to the variation in the moisture content in the biomass wood chips. The goal is to design a process control system that allows the combustion process to be run with optimal energy output per kg of biomass wood chips by using the measured moisture content of the biomass wood chips. The project was divided into two major phases. Phase I involves performing a study to understand the biomass combustion system and the KSM Multistoker XXL. The following are the milestones for Phase I:

- Conduct a literature review on biomass combustion systems and the KSM Multistoker XXL and describe the combustion reaction in the furnace using physical and chemical equations.
- Describe the process regulation of the biomass combustion system using SIPOC (supplier, input, process, output, and customer) process map and the Proportional Integral Derivative (PID) regulation.

Phase II involves the study of the available moisture content measurement methods and the selection of the most suitable technique for this research case. In addition, a process control system was designed using process design building blocks and relevant lean six sigma tools. The milestones for Phase II are:

- Map possible methods for measuring the moisture content in biomass wood chips.
- Define selection criteria for choosing the most suitable moisture measuring technique.
- Provide technical solutions for the installation of moisture measurement techniques in the KSM Multistoker XXL with measured moisture content as an input to the PID regulation of the furnace.
- Suggest lean tools for optimal process control and improvement.

1.4 Structure of Research

This chapter of the research provides a background for the research through the review of current knowledge and identification of gaps in current knowledge. The aim of this thesis and the research objectives are then defined to fill the gap in current knowledge.

The other chapters in this research provide more detailed description of the research area, methodological approach, experiments, and results. They are structured as follows:

- **Chapter 2: Literature Review**
  This chapter provides an overview of current knowledge in the research area. Sources utilized for the literature review include journals, articles, books, reports and some company websites.
- **Chapter 3: Methodology**
  This chapter further elaborates on the aim of the research. It also outlines and describes the research methods and design.
- **Chapter 4: Results and Discussion**
  This chapter presents the discoveries and outcome of the research with their corresponding meaning or interpretation.
- **Chapter 5: Conclusion**
  This is the final chapter of the research where conclusions are made regarding the research findings. The findings are discussed in relation to the problem description and the knowledge gap the research intends to fill. The limitations encountered during the research were discussed and recommendations for future research related to the study were also highlighted.

2 Literature Review

2.1 Biomass

Biomass is capable of supplying a great portion of the global renewable energy demands while also providing employment [15]. However, this potential can be limited by expertise, management capacity in building an efficient and sustainable biomass supply network and the level of advancement of bioenergy systems [16].

Biomass is a relatively cheap energy source with less greenhouse gas impact, and it is nearly CO_2 neutral. Recently, there has been an increased use of biomass as a substitute for conventional fossil fuels [17]. In the heating of buildings, biomass is burnt either in stoves and furnaces to radiate heat directly into the rooms or the biomass is burnt in a boiler which is connected to a water circuit that supplies thermal energy in the form of hot water in insulated pipes for the provision of heat [18]. However, biomass mostly has higher moisture content and lower heating values which makes them differ significantly from conventional fossil fuels like coal or petroleum [17].

Bioenergy provides a great avenue for the improvement of energy supply security in several nations, especially for countries with plenty forests and established district heating structures [16].

2.2 Heating Systems

The primary function of a heating system is to warm a closed area, such that a thermal equilibrium is reached between the human body and its environment. This makes the residents of the room thermally and physiologically comfortable [3]. Heating systems influence the air temperature and the radiant temperature of surrounding materials. A very important indicator that an environment is thermally comfortable is the operative temperature, which is the weighted average of the air and radiant temperature of surrounding surfaces [3]. The use of central heating systems to heat public spaces and rooms can be traced back to the 4th century BC in Greece and later became popular in palaces, large villas and homes of upper class and wealthy Roman merchants [3]. Hot air and smoke were generated from furnaces or fireplaces and used to heat up the rooms directly above and other rooms through ducts in the wall. In the late 19th century, the advancement of technologies associated with steam boilers, cast iron processing and the manufacture of quality copper provided an avenue for the development of hydronic central heating systems where water or steam is used for heat transfer in heating systems. By the year 2011, several state-of-the-art technologies like oil fired boilers, biomass furnaces and solar fireplaces could be used to ensure a thermally comfortable and safe environment for inhabitants at a reasonable rate. This was especially due to the technological strides made in control and automation engineering which made heating systems more intelligent by the use of sensors to meet several operational requirements [3].

2.2.1 Classification of Heating Systems

Heating systems can be classified based on the source of energy, location of the heat producing and transporting equipment and the method of heat transfer. The source of energy can be solid fuels, gaseous fuels, liquid fuels, solar radiation, electricity, or waste energy. Based on location of equipment, heating systems can be grouped into local, central and district heating systems. The heat carrier can be water, air, or electric current and heat transfer can be done through convection, radiation or by releasing heated air straight into the room [3].

2.2.1.1 Local Heating Systems

Local heating systems only generate heat in the room to be heated. This form of heating system requires no distribution or transportation system but directly emits heat into the surrounding areas. Although these type of heating systems have simple installation and operation with low initial costs, they hardly achieve uniform temperature distribution in the room, and they are extremely difficult to regulate to precision [3].

Open Fireplace

Open fireplaces for heating are very old heating systems that are easy to construct but of low efficiency, around 20%. During operation, about 80% of the produced heat is lost and discharged through the chimney. More modern fireplaces are being designed to help reduce lost heat through the chimney, thereby increasing the efficiency [3].

Modified Fireplace with Circulation Chamber and Embedded Heat Exchangers

The efficiency of open fireplaces can be improved by the installation of a cavity through which air is circulated. The cold air in the room goes through the inlet of the circulation chamber at the bottom of the firebox, circulates behind the firebox, exits the chamber, and returns to the room through an outlet close to the room ceiling. When tightly fitted glass doors and a blower which forces air through the circulation chamber are integrated into the system, then the efficiency of these fireplaces can be increased to about 30%. The efficiency of this fireplace can further be improved to 70% through the installation of internal heat exchangers mounted in the flue gas channel, where they absorb great amounts of heat that would have been wasted through the chimney. Water or gas passing through the heat exchanger is circulated through a network of pipes to radiators or under floor heating systems [3].

Wood and Pellet Burning Stoves

Wood burning stoves with regulated air flow can provide efficiency reaching around 75%. Wood burning stoves provide a high heating effect for a short period of time which results in sudden temperature changes in the environment. However, pellet burning stoves are more efficient, about 85% efficient and provide a means for automatic pellet ignition and pellet feeding. Automatic pellet feeding from storage allows for continuous operation of the pellet stoves for a long period depending on the size of the stove and on the surrounding temperature. Usually pellet stoves have thermostats that switch them on and off and a computer system to adjust the feed rate of pellets. A regular room stove provides heating to the surrounding through forced-air ventilation while others have a boiler for heating water that circulates to heat radiators in other rooms [3].

There are few disadvantages of wood biomass heating systems, including: the requirement of a storage area and the incomplete combustion of wood produces dangerous emissions including particulate matter, carbon monoxide, nitrogen oxides, sulfur oxides and volatile organic compounds [3].

2.2.1.2 Central Heating Systems

Central heating systems produce heat from an equipment that is installed in a section of the building to heat up major areas of the building. Central heating systems can be grouped into wet systems (hydronics), which uses water as a heat transfer medium, and forced-air systems where heat is distributed through a room using a fan. Central heating systems are also made up of three separate parts: the equipment that produces heat, the distribution medium and the control system [3].

Heat is produced and transferred to the transfer medium by gas or oil boilers, biomass boilers, heat pumps or solar thermal collectors. Water is mainly used as the heat transfer medium, and it is distributed through pipes with the use of pumps. The heat energy is transmitted into the areas where heat is needed through radiators, convectors, or a piping network underfloor that radiates heat into the heated area. The control system comprises sensors, actuators and software programs that control the switching of the boiler on and off to achieve the set room temperatures [3].

In forced-air central heating systems, the heat producing equipment is the gas, oil or biomass furnace and air is used as the heat transfer medium. The heated air is then distributed through duct systems into the rooms where heating is required using diffusers placed on the walls or ceilings [3]. Air blowers provide the required pressure to the heated air to overcome the resistances caused within the duct system. A control system is also required in forced-air systems to switch the boiler on and off. Forced-air central heating systems can heat a room more rapidly than hydronic systems and this is a major advantage especially in large spaces that require quick adaptation to certain temperature requirements [3].

2.2.1.3 District Heating Systems

District heating systems distribute heat to several buildings through a network of pipes with water as the transport medium (hydronic system) [3]. The hydronic system is made up of a boiler, a burner, a water pump for circulation, a fuel storage tank, piping systems, radiators and several control devices and safety equipment. District heating systems make use of heat and fuel sources that would have been wasted to provide room heating and hot water to buildings in a particular area through a heat network. Heat in this system can be obtained from a cogeneration fossil fuel plant, biomass power plant or geothermal heat pump. District heating plants provide higher efficiencies, cheaper costs than alternative power and are better for the environment in terms of pollution control[3, 9].

2.3 Biomass Combustion System

The design of a biomass combustion system and its operating parameters are dependent on the properties of the biomass that will be used. Properties like the moisture content, heating value and composition of minor constituents such as chlorine, sulfur and nitrogen are important to consider when designing a biomass combustion system. These unique biomass properties can provide certain advantages and pose several challenges to the combustion process. A very good understanding of the physical and chemical processes that occur during biomass combustion can contribute to a more efficient and improved heating system [17].

A biomass combustion system is made up of the combustion chamber, the fuel feeding system, the heat transport medium, the heat exchanger, and the control system [14]. The most common types of combustion chambers have air supplied through three channels. The first channel provides air supply during the ignition of fuel, after which the channel closes. The second source is used to supply the primary air that flows around the fuel to maintain combustion. The third air channel is used to supply air needed for secondary combustion [19].

2.3.1 KSM Multistoker XXL

The KSM Multistoker XXL is a biomass combustion system designed to use different types of fuel with varying levels of moisture content. Wood pellets with 8% moisture content and wood chips with 20% moisture content were used for testing and approval of the KSM Multistoker XXL by the Danish Technology Institute. However, biomass with higher moisture content percentages could be used to fire the KSM Multistoker XXL but this would result in varying heat exchange performance and system efficiency [10].

The KSM Multistoker has a large combustion chamber coupled with a PCT400 modulating oxygen control that is designed to burn efficiently a great portion of the biomass that is injected into the furnace and ensure perfect combustion. The PCT400 control of the KSM Multistoker is a full modulating O_2 controller with integrated PID regulator. The KSM Multistoker has a flame damper for automatic feeding of biomass and is also furnished with a water-cooled burn head that has hydraulic moving fire grate which is of great advantage when burning biomass with high ash and clinker content. It also has two ash augers for transporting ash for disposal [10].

2.3.2 Combustion Reaction in the Furnace

Several physical and chemical processes occur simultaneously when fuel burns in a combustion chamber. Some of these processes are drying and heating of fuel, separation of volatile matter, flaming combustion of pyrolysis products and combustion of the solid combustible residue [5].

2.3.2.1 Physical Equations Governing Reaction in the Furnace

Once biomass is subjected to heat in the presence of oxygen, several processes begin to occur simultaneously in the combustion chamber. Firstly, heat transfer occurs at the surface of the biomass through conduction and the temperature in the biomass continues to rise until the pyrolysis temperature is reached. When the pyrolysis temperature is reached then thermal decomposition of the biomass starts and heat is transferred inside the biomass through conduction and through the pores by convection. Close to the end of the pyrolysis process after volatiles are released, the homogeneous reactions occur and the char ignites [20]. The increase in the heating rate and quantity of biomass and the decrease in biomass porosity results in higher volatiles and char ignition temperature [20]. The thermal decomposition of biomass during a combustion reaction is usually separated into two phases:

$$\text{Solid} \longrightarrow \text{Char} + \text{Gas} \tag{1}$$

$$\text{Char} \longrightarrow \text{Gas} + \text{Ash} \tag{2}$$

The combustion reaction in the combustion chamber can be modelled using the continuity, momentum, and species transport equation [20]. They are given below:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho W_i) = 0 \tag{3}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}\left(\rho_f W_i W_j\right) = \frac{\partial}{\partial x_i}\left(\mu_{eff}\frac{\partial W_j}{\partial x_i}\right) - \frac{\partial p}{\partial x_j} \tag{4}$$

Species transport equation:

$$\frac{\partial}{\partial x_i}(\rho W_i Y_k) = \frac{\partial}{\partial x_i}\left[\rho\left(D_{m,k} + \frac{\mu_{eff}}{\rho\sigma_t}\right)\frac{\partial Y_k}{\partial x_i}\right] + R_k \tag{5}$$

The rate of reaction of the thermal decomposition of biomass is governed by the first-order Arrhenius law.

2.3.2.2 Chemical Equations Governing Reaction in the Furnace.

Combustion is one of the thermo-chemical processes through which biomass can be used to produce energy by the application of heat and in the presence of oxygen. About 90% of the total renewable energy generated from biomass is produced through the process of combustion [21]. Biomass furnaces can combust several types of biomasses like wood, dry leaves, hard vegetable shells and rice husks [21].

In combustion, biomass is mixed with oxygen in a high temperature environment to form carbon dioxide, water vapour and heat.

$$\text{Biomass} + \text{Oxygen} + \text{Water (liquid)} \longrightarrow \text{Carbon Dioxide} + \text{Water (gas)} + \text{Heat} \quad (6)$$

An approximate chemical equation for the combustion of biomass is given below:

$$CH_{1.44}O_{0.66} + 1.03\ O_2 + \text{Water (liquid)} \longrightarrow CO_2 + 0.72\ H_2O + \text{Heat} \quad (7)$$

Combustion in biomass occurs due to the exothermic reaction between the biomass and oxygen. The main products released from combustion are H_2O and CO_2. Also, due to the preexisting water content in the biomass before combustion, water (vapour) is released along with the hot fumes [22].

The heat produced depends majorly on the type of biomass used but can also be influenced by many other factors. The average thermal energy produced from the combustion of biomass is 20 MJ/kg of biomass [21]. The combustion of biomass is an exothermic process where chemical energy is released and is converted into either mechanical or electrical energy [21].

Biomass is characterized by its ultimate and proximate analysis. The ultimate analysis reports the weight percent of carbon, hydrogen, nitrogen, sulfur, and ash. The proximate analysis reports the moisture content, volatile matter, and fixed carbon. Majority of biomass have a low High Heating Value (HHV) of about 20 MJ/kg because they contain a fraction of carbon below 50%, and a greater portion of the remaining fraction is oxygen [23]. The ultimate analysis and heating value of spruce wood and spruce trunk bark are shown in Table 1 below [24].

Table 1. Ultimate analysis and HHV (MJ/kg) of spruce wood and spruce trunk bark.

	C	H	O	N	Ash	HHV
Spruce wood	51.5	6.2	41.3	0.4	0.4	19.7
Spruce trunkbark	54.2	6.6	36.0	0.5	2.7	21.5

2.4 Combustion Control System

A control system is a connection among several components which creates a system configuration that will result in a desired system response. In control systems, a cause-effect and input-output relationship is assumed between components in the system where the processing of an input signal provides a corresponding output signal variable [25].

An open-loop control system utilizes a controller and an actuator to obtain the desired system response without any feedback into the system [25].

In contrast, a closed-loop control system performs a comparison between the actual output and the desired output response. The measured output is referred to as the feedback signal. A closed-loop feedback control system is a control system that uses a function of a defined relation between the process output and the reference input to control the process and reduce errors. The controller is a system component that reduces or adjusts the error by triggering the actuator to tune further tune the process [25].

Feedback control systems can have a single feedback loop or contain multiple loops. When feedback control systems have multiple loops with each loop having its controllers and sensors they are referred to as multi-loop feedback control systems. As systems continue to increase in complexity and the interrelationship between controlled variables continue to rise, multivariable control systems have also become common [25].

2.4.1 Basic Elements of a Closed-Loop System

The functions of the elements constituting a closed-loop system are given below:

1. Process

   The process is the system that contains the variable to be controlled. For instance, a biomass combustion process with the variables of air flow or feed rate of wood chips to be controlled [26].

2. Measurement element

   The measurement element produces an output signal related to the variable condition of the controlled process. For instance, in the design of a process control system for combustion regulation by moisture measurement in biomass wood chips, the moisture measurement sensor produces an output signal depending on the moisture content in the biomass wood chips [26].

3. Comparison element

   This element compares the required value of the controlled variable with the value obtained when measured. When there is a difference between the value required and the measured value obtained, an error signal will be generated and launched. However, if there is no difference between the required value and the measured value there will be no error signal and no control action would be initiated [26].

4. Control law implementation element

   This element determines what control action to initiate when there is an error signal received. The control law initiated by the element could produce a signal that turns on or off a switch. Control laws include the proportional mode where the signal produced is proportional to the error or the integral mode where the control signal continues to increase if an error remains and the derivative mode where the control signal is proportional to the rate of the change of error [26].

The term controller is used to depict the combination of the comparison element and the control law implementation element [26]. A major type of controller commonly used in industrial process control is the proportional-integral-derivative (PID) controller. PID control systems have been used for a long time in various industries to control processes and systems due to its simplicity and low design cost [27]. PID controllers are the most commonly used industrial controllers [28]. When the values of the PID terms are interpreted in relation to time, ‘P’ depends on the present error, ‘I’ depends on the build up of past errors and ‘D’ is an estimation of future errors depending on the present rate of change. If the three parameters in the PID controller algorithm are properly tuned, then the controller can provide adequate control for the specific process. However, it is a quite difficult task to set the PID gains [27]. A conventional PID controller is utilized in a closed loop system in order to achieve the control objectives through the modification of the system inputs [28].

5. Correction element

   The correction element produces a change in the process with the goal of correcting the controlled condition. An actuator is a correction element that provides the ability to perform the control action. Examples of correction elements in a biomass combustion process can include electric motors or valves which can increase feed rate of wood chips or air flow rate [26].

2.5 Process Description using Proportional Integral Derivative Controller

In several industries, temperature control has become a critical issue in various processes. For instance, temperature control in heating systems is useful in bioenergy, metallurgical, pharmaceutical, and chemical industries. The PID control algorithm is very common in its application in diverse temperature control functions due to its simplicity and versatility [29]. Conventional PID controllers have been improved over the years, starting with controllers based on relays, electric motors, hydraulic and pneumatic systems to the use of microprocessors. Some PID tuning methods used to obtain the PID control parameters include the setpoint overshoot method, the direct synthesis method, Nelder Mead method, Ziegler Nichols method, and Cohen-Coon method [29, 30]. There have also been several software developments in the field of PID controllers such as the inclusion of gain scheduling of PID controllers which continuously adjust the gains of the PID algorithm during process control. Also, computing environments like MATLAB and COMSOL are now used for implementation and simulation of PID control algorithms [29]. For instance, the PID Controller add-in within COMSOL can be used to regulate the inlet velocity of the gas with lower oxygen concentration within a combustion chamber where two gas streams mix in order to achieve the desired total concentration at the ignition point [31].

PID controllers are made up of Proportional, Integral and Derivative controls. The proportional control allows for faster entry into the steady state, the integral control helps to reduce overshoot in the steady state and the derivative control helps to bring more stability into the system [30]. Figure 2 below shows a single-input single-output control loop that consists of the PID controller and the controlled plant [30].

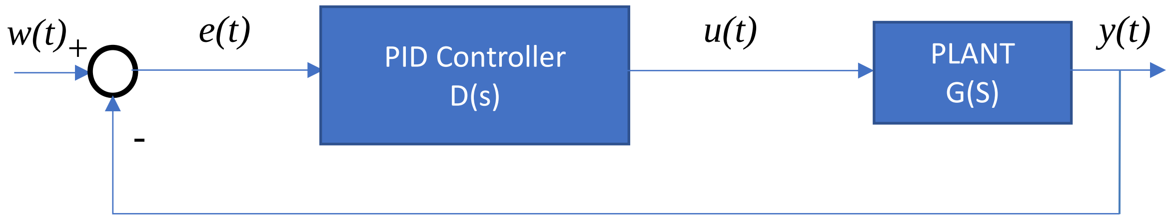

Figure 2. A Single-Input Single-Output (SISO) control loop with PID controller

Where *w(t)* is an input signal to the controlled plant, *e(t)* is the system error, *u(t)* is the controlled input, *y(t)* is the output signal, *D(s)* is the transfer function of the PID controller and *G(s)* is the transfer function of the controlled plant. The equation of a standard PID controller is given below [30]:

$$u(t) = k_P e(t) + k_i \int e(t)\, dt + k_d \frac{de(t)}{dt} \qquad (8)$$

It can also be written in the form of transfer function as:

$$D(s) = \frac{U(s)}{E(s)} = k_P + \frac{k_i}{s} + k_d s \qquad (9)$$

Where U(s) is the transfer function of the controlled input, E(s) is the transfer function of the system error e(t), k_P, k_i and k_d are the proportional gains, integral gains, and derivative gains. A block diagram of the PID controller is given in Figure 3 based on the equation of transfer function [30]:

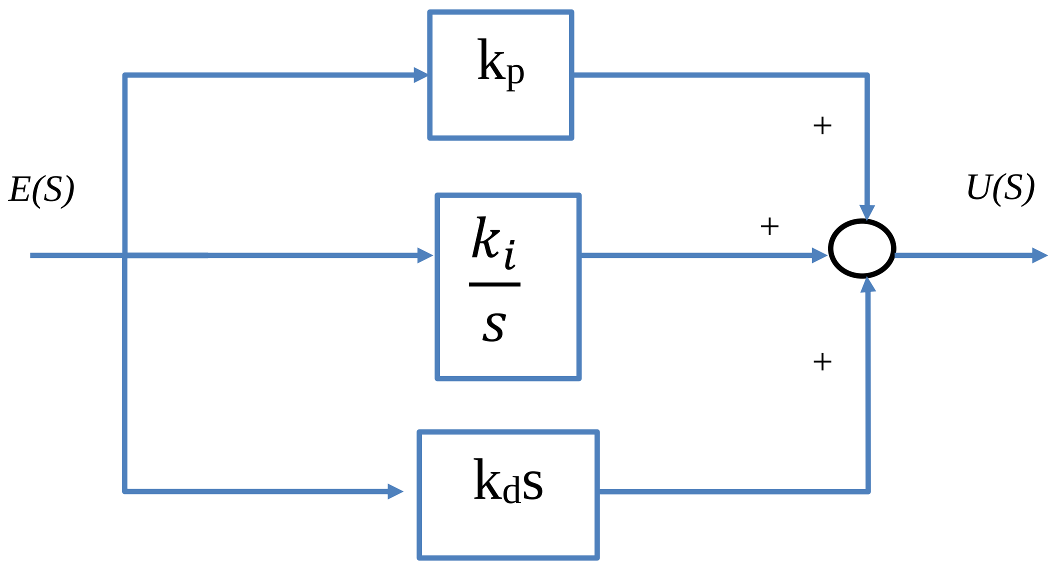

Figure 3. A block diagram of a PID controller

In the combustion control system, a sensing or measurement element will be implemented to provide feedback to the control loop. The moisture content present in the biomass wood chips would be measured using the moisture measurement element and an output signal would be produced. This output signal would serve as the input to the PID controller. The PID controller implements the control law which compares the measured moisture content with the set point and then gives a command to the correction element to effect a change in the combustion process [28].

2.6 Process Description using SIPOC Process Map

SIPOC (suppliers, inputs, process, outputs, customers) is a tool that outlines the inputs and outputs of processes in a chart. It is a tool for recognizing the variations between the process requirements and what the supplier provides and variations between the customer expectations and the process deliverables [32]. The elements of the SIPOC are further explained below [32]:

- Supplier: These are entities, organizations, companies, or people that provide resources that will be utilized in the process.
- Input: These are materials, substances, information, or resources that are provided by the suppliers and are required for use in the process.
- Process: A series of steps that converts or transforms inputs to output.

- Output: Products and substances released from processes and needed by customers or another process.
- Customers: People, processes, clients, individuals, companies, organizations in the next phase that receive the output of the previous process.

SIPOC uses a matrix for the identification, characterization, measurement, and evaluation of processes. It provides a means for the analysis and identification of process improvement areas. The SIPOC method is helpful in the increase of the efficiency of processes and the remodeling of processes when it is used to evaluate these processes at a higher level [33]. The suppliers, inputs, processes, outputs and customers for the KSM Multistoker XXL are shown in Table 2.

Table 2. A SIPOC chart for the KSM Multistoker XXL

<table>
<tr><th>Supplier</th><th>Input</th><th>Process</th><th>Output</th><th>Customer</th></tr>
<tr><td rowspan="2">Wood supplier
KSM Stoker</td><td>Biomass / Wood Pellets (Spruce)
Air
Moisture content in wood
KSM Multistoker (Combustion furnace)</td><td>Combustion</td><td>Hot fumes
Carbondioxide
Water
Energy
Ash/Char particles</td><td rowspan="2">District
Companies
Buildings</td></tr>
<tr><td>Cold/Warm Water
Hot fumes
Pump
Valves</td><td>Heat Exchange</td><td>Hot water
Heat energy</td></tr>
</table>

A process design flowchart can also be used to highlight details regarding the unit operations in each process and show the feed and product material flow details for various processes [34].

As shown in Figure 4, the first process is the combustion process where biomass with moisture content is mixed with oxygen in a high temperature environment to release hot fumes [21]. The second process is the heat exchange process between the hot fumes and cold water. The resulting hot water is then transmitted to customers for heating of buildings while the cold fumes are released to the environment [3].

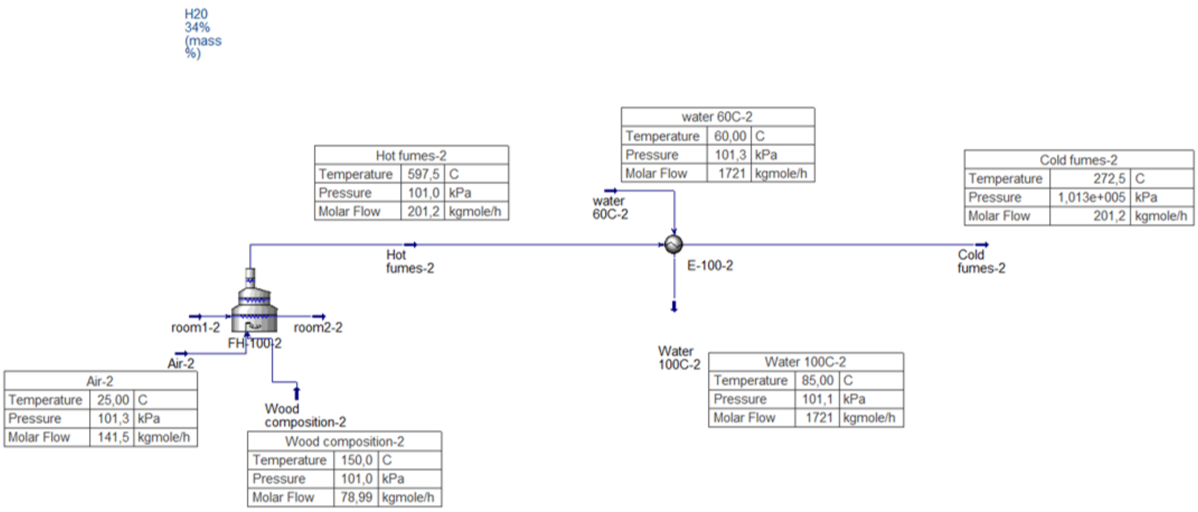

Figure 4. Process design flowchart for the KSM Multistoker XXL.

The moisture content of the biomass used as fuel in the KSM Multistoker XXL is vital in determining the furnace exit gas temperature, the heat transfer performance at the heat exchanger, and the consumption rate of the biomass which are critical factors in establishing the overall system efficiency [8]. As the moisture content in biomass increases, the hot gases released from the combustion process reduce in temperature. However, the heat transfer performance between the released gases and the cold water improves thereby lowering energy loss and improving system efficiency. If the biomass contains a low percentage of moisture content, then the temperature of the hot fumes released from the combustion increase but the heat exchange performance is low and consequently reducing the system efficiency [8].

Hence, it is very important to measure the available moisture content in the biomass feed prior to burning in the combustion chamber in order to optimize the overall system efficiency.

2.7 Moisture Content Measurement

Moisture content is an important determinant of the quality of biomass wood chips. It affects the net calorific value and the rate of biomass consumption. The moisture content can be measured through direct or indirect methods. Direct methods involve the measurement of moisture content through the direct analysis of the biomass wood chips while the indirect methods perform measurements on the flue gases that are formed. The standard method for measuring moisture content in biomass is the oven-drying technique which involves drying the biomass at 105°C until it settles at a constant weight [35]. This method is mostly used because it measures the moisture content in the biomass more precisely and accurately. However, the oven-drying method takes a minimum of 24 hours before the moisture content of the biomass can be measured and this is a major disadvantage for biomass plants who need to feed the sampled biomass heap into the boiler [35]. Therefore, it is necessary for moisture content measurement techniques to be able to rapidly determine the moisture content in a biomass feed in addition to being precise and accurate [36]. The moisture content is a major factor that determines the calorific value of biofuels. A high moisture content in biomass causes the combustion process to release less heat because much of the energy is used to evaporate water. The moisture content is also very important in determining how the combustion of biomass in the furnace should be regulated so that the efficiency of the furnace is improved, and emissions are brought to a minimum [8].

2.7.1 Factors that Affect Moisture Content Measurement

Moisture content measurement methods measure properties in materials that are affected by variation in moisture content. Therefore, the methods for measuring moisture content in biomass must be based on properties that can both be detected and that differ between wood and water [37]. Usually, however, the measured properties are affected by the properties and changes in the wood. At approximately 23% moisture content in wood, the fiber saturation point is reached. Above the fiber saturation point, water molecules are less tightly bound to the wood, and this affects some of the measured properties [35].

Also, different types of wood have slightly different properties which can affect the moisture content measurements in biomass. However, the degree to which the moisture content measurements are affected depends on which properties in the wood is measured [38].

Another factor that influences the measurement result is the temperature of the biomass. This is because many properties of water and wood as well as the relationship between these properties are affected by temperature [35]. A temperature change by a few degrees above the freezing point of the biomass leads to small changes in the wood and water properties. These changes are small when compared with the changes that occur when the water turns into ice. There is a great difference between the properties of ice and liquid water because the molecules in ice become more tightly bound together with less opportunity to move and this affects both their mechanical and electrical properties [35, 39]. Also, the properties of ice can sometimes be similar to those of wood which makes it difficult to distinguish them [35].

For moisture content to be determined with certain measurement methods, the amount of water molecules present in the sample must be detected. In these cases, the density of the sample must be known [36]. A given amount of water molecules means a higher water content in a less dense material than it does in a dense material [35]. In addition, other substances such as impurities or chemicals in the sample can affect the measurement. For instance, in neutron spectroscopy which is a spectroscopical method of measurement based on electromagnetic radiation, the impurities can have properties that resemble those of water and thus affecting the measured properties to a great extent [40].

2.7.2 Methods of Moisture Content Measurement

There are several methods for measuring moisture content. Many of the moisture measurement methods have existed for many years while others are still in the research phase. For instance, the resistance meter which is an electrical method of moisture content measurement has been around since the year 1930 and the drying oven method has also existed for many years [41]. The different moisture measurement techniques are shown in Figure 5. Each measurement technique has its own unique advantages and disadvantages.

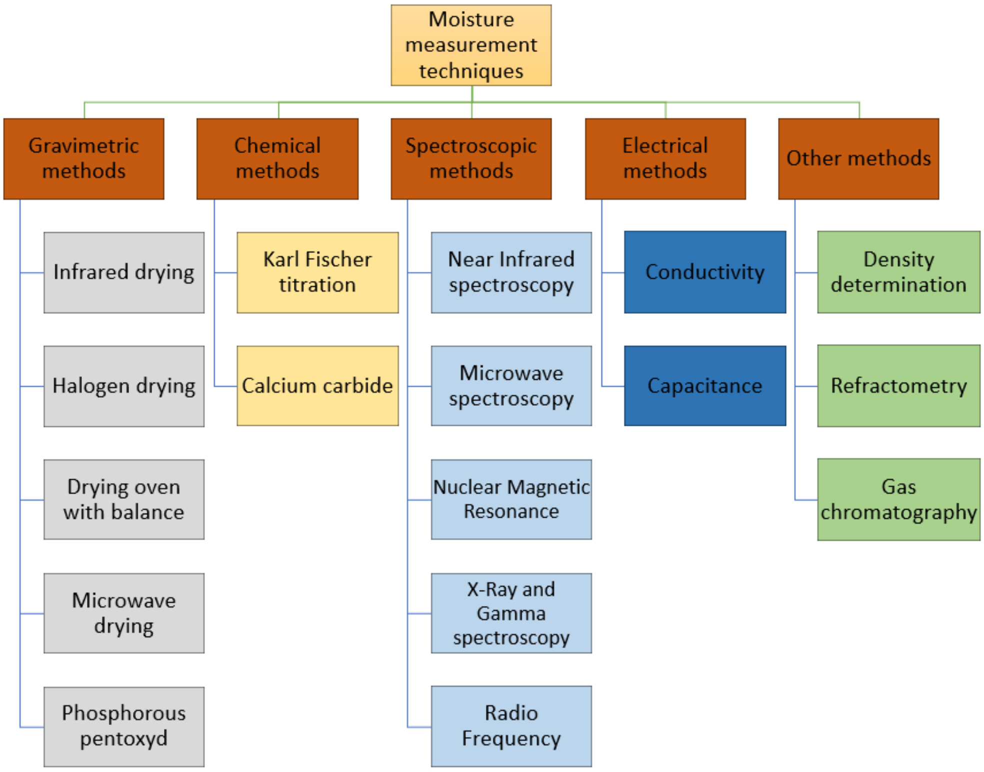

Figure 5. Moisture measurement techniques

2.7.2.1 Thermogravimetric Methods

The standard and most common method used in measuring moisture content is the thermogravimetric method. This method involves weighing samples of the biomass material whose moisture content is to be determined to get the combined weight of the water and biomass (wood chips) [42]. The biomass sample is put in a drying oven and weighed again to obtain the weight of the dry mass. The moisture content in the biomass sample can then be determined by relating the mass after drying to the original weight of the sample [42].

The Swedish Standard and the Timber Measurement Council recommends that the drying oven is kept at a temperature of 105±2˚C until the weight has stabilized and no change of more than 0.2% of the total weight occurs in a period of 30 minutes. It usually takes about 20 hours for the weight to stabilize. The drying temperature and drying time influence the moisture measurements greatly [35].

Thermogravimetric methods are referred to as the classical methods. The method has an average error of 2% which is smaller than many other methods. However, this method has certain flaws including the vaporization of other volatile substances other than water from the biomass sample when heated. Biomass samples dried at higher temperatures of up to 105˚C lose more weight than samples dried at lower temperatures. However, a low drying temperature will lead to a longer drying time. It is therefore important to establish a balance between the two parameters [42].

Thermogravimetric methods are simple and relatively cheap. The method is independent of the temperature of the sample. Also, the accuracy of the method is not limited by the moisture range of the sample since the moisture is eventually dried away. However, moisture content measurement can take a long time due to the time required for drying. Also, this method is personnel intensive and requires many samples to be taken from the biomass batch in order for the results to be representative of the entire batch [43].

Thermogravimetric methods include the drying oven method, infrared, halogen, and microwave drying. These methods serve as reference methods for indirect moisture measurement methods. Among the thermogravimetric methods, the drying oven method has the longest tradition as a standard method and obtains the measured values with the best reproducibility. The infrared and microwave drying methods are becoming more popular because of the shorter time in obtaining the measured values. However, they cannot be used for all substances due to the risk of decomposition [35].

Drying Oven

Material moisture is physically bound water in a solid substance that can be removed from the substance by drying without destroying its structure. The mode of action of the thermogravimetric method is based on the quantitative separation of water from the sample. In this method, the total mass of the sample to be measured is dried until the state of equilibrium is reached [44]. To ensure that the measured moisture values are highly reproducible, material-specific sampling and preparation is necessary and this takes a great amount of time. A suitable number of random samples is required for achieving an accurate moisture reading. The end of the drying does not equal the complete elimination of water but the attainment of a state of equilibrium between the vapour pressure in the sample and the vapour pressure in the drying oven. The mass is considered to be constant when the mass difference between two consecutive weighing, carried our several hours apart is less than 0.1% of the last mass determined. The drying temperature for several materials is 105±2˚C [42].

Infrared Drying

Radiant heaters used for infrared drying emit radiation in the infrared range of 0.77 - 340µm. The radiation intensity increases with increase in temperature of the radiator. When the temperature increases, the peak wavelength moves in the direction of the short-wave spectral range. Many substances absorb infrared radiation more than visible light. Therefore, the heating of the sample is not only dependent on the radiator temperature but also on the correspondence between the radiator emission spectrum and the absorption spectrum of the sample [42].

In infrared drying, the sample is placed on a balance beneath the radiator. When the mass remains relatively constant or after a stipulated time, the mass loss and thus the moisture content is calculated. In some simple infrared drying devices, a separate weighing must be carried out. The infrared radiation is absorbed and reflected on the surface of the sample. The heating can be increased when wavelengths with higher intensity are emitted where water has typical absorption bands. For example, in absorption bands like 1.94, 2.95 and 3.5 µm, the penetration depth of radiation depends on the absorption and reflectivity, as well as the colour and surface texture properties of the sample [42]. Heat is transferred from the surface to deeper layers by heat conduction. If the temperature is too high, volatile components can be expelled and the sample can decompose. Small amounts of the sample are prepared in thin layers when using infrared dryers as a thick layer or inhomogeneous distribution of the material in the sample tray can lead to uneven heating. This further results in measurement errors due to incomplete drying or an increase in the drying time [42].

The infrared drying method has a comparable accuracy to the drying oven method and is less time-consuming. The measuring times can range between 3 to 30 minutes depending on the moisture content and the consistency of the substance [42].

Microwave Drying

Microwave drying helps to eliminate the disadvantages of the drying oven method by accelerating the drying process, lowering energy consumption, and enabling homogeneous drying. Microwave drying produces a completely different temperature distribution in the test sample. The temperature in the test sample rises much faster at the areas of greatest moisture which results in greater losses in those areas than on the surface. During the microwave drying process, a temperature gradient forms from the inside of the sample to the outside and this causes a large part of the water in the sample to be released very quickly. Also, a high vapour partial pressure develops inside the sample and through diffusion, the water from inside the sample can reach the surface very quickly and evaporate on the surface thereby causing it to cool down. The microwave chamber is heated up by the heat emitted by the test sample [42].

In conventional microwave ovens, the energy transmitted is generated by a magnetron at 2.45 GHz. Since, an even distribution of energy in the microwave is difficult to achieve, several microwave ovens have rotating sample plates and buttons for adjusting the microwave power. Microwave drying is mostly used for quality control in the food, chemical and paper industries. The method is less suitable for almost dry and temperature sensitive samples due to the risk of burning or decomposition. Experiments have found that the reproducibility achieved is similar with the results of the drying oven method and the time taken for measurement can be reduced from 130 minutes to 10 minutes [42].

Halogen Drying

Halogen drying method makes use of halogen lamps which heat to a lower temperature than the conventional drying oven method but still dries the samples more rapidly. Halogen drying provides uniform surface heating of the sample to be measured due to the halogen lamp geometry [45]. The heating element is made up of a glass tube filled with halogen gas that works with a gold-plated reflector that ensures the uniform distribution of the thermal radiation over the sample surface [43]. Halogen drying is more advantageous than other thermogravimetric methods when measuring moisture content. It is easy to use and cost effective. It also provides quick, accurate and repeatable measurements [45].

Phosphorus Pentoxide

Phosphorus pentoxide is set together in a closed system with the sample whose moisture content is to be measured. The phosphorus pentoxide absorbs the water vapor which vaporizes from the sample when it is heated. The weight gain of the phosphorus pentoxide is used to measure the moisture content in the sample [44, 46].

2.7.2.2 Chemical Methods

Karl Fischer Titration

The Karl Fischer titration is a popular analytical method for determining moisture content in various samples. The method is based on the reaction between iodine and water in an alcoholic solution or the oxidation of sulfur dioxide by iodine in a methanolic hydroxide solution. Methanol (CH_3OH) is the most common solvent used in Karl Fischer titration [47].

$$H_2O + I_2 + SO_2 + CH_3OH + 3RN \longrightarrow [RNH]SO_4CH_3 + 2[RNH]I \quad (10)$$

RN in the chemical equation above represents a base. The main advantage of the Karl Fischer titration is its high selectivity to water and only the water content is determined. The oxidation reaction consumes water since iodine and water are consumed in a 1:1 mole ratio in the Karl Fischer titration. When the reaction consumes all the water present, the presence of excess iodine is detected by an indicator electrode. The percentage of water is then calculated based on the I_2 in the Karl Fischer titrating reagent and the amount of reagent consumed. This method is fast, accurate and has a wide measuring range. However, the processes involved in sample preparation is time consuming [47].

Calcium Carbide Method

Calcium carbide method is a direct method for the determination of moisture content in samples. In this method the water in the sample is converted into a gaseous product by a chemical reaction and the moisture content present is evaluated through the quantitative measurement of the gaseous product. The calcium carbide method is based on an exothermic chemical reaction where the decomposition of calcium carbide occurs due to its reaction with water [48]. The calcium carbide reacts with the water content of the sample material in the sealed vessel when the bottle is shaken by hand [49].

$$CaC_2 + 2H_2O \longrightarrow Ca(OH)_2 + C_2H_2 \quad (11)$$

Acetylene gas evolves from this reaction in a steel bottle and the pressure is measured. Assuming ideal gas behavior and if the temperature and volume of the reaction bottle is known, the acetylene pressure can be related to the amount of moisture content present in the sample. Usually, producers of moisture measuring devices operating with this method provide a pressure-moisture conversion table which is established empirically so as to achieve greater accuracy in the moisture measurement [48].

2.7.2.3 Spectroscopic Methods

The spectroscopic method is based on electromagnetic radiation of different wavelengths, ranging from the radio frequency radiation with the longest wavelength to the microwave, radar, infrared, X-ray, and the gamma radiation with the shortest wavelength. All wavelengths affect and are affected by the material they strike against [35]. However, the reason why the characteristics of the measurement methods working with the electromagnetic radiation technique may vary is because different wavelengths affect the material at different levels; some affect bonds between atoms, while others affect the atoms themselves. There is also a technique based on ultrasound which is quite similar to the electromagnetic radiation, where sound waves are used to illuminate the sample instead of light [43].

Near Infrared (NIR) Spectroscopy

NIR spectroscopy method is based on the fact that chemical bonds in a sample can absorb radiation at certain wavelengths that are specific to that sample. The sample to be measured is irradiated with two or more different wavelengths, where one wavelength is absorbed by chemical bonds in the water molecules and the other wavelength is not absorbed by the biomass or the water molecules. The ratio between the two wavelengths is then used as a measure of the moisture content in the sample [35, 39].

NIR spectroscopy uses wavelengths in the infrared spectrum between 780 – 2,500 nm. NIR spectroscopy sensors can either use radiation of a few fixed wavelengths or use multi-wavelength technology where it chooses the most suitable wavelengths. Multi-wavelength technology (scanning NIR) works over the entire NIR spectrum and then chooses which wavelengths are the most suitable. With NIR spectroscopy, the transmission or reflectance can be measured and related to the moisture content in the sample. In transmission, the light source that irradiates the sample is placed on one side and the detector that measures how much radiation passed through the sample is placed on the other side. In reflectance, the proportion of the radiation that is reflected back is measured, therefore the transmitter and the detector are placed on the same side of the sample. NIR can be used in several industries like the food, biofuel, pharmaceutical, petroleum and paper industries [35, 39].

The wavelengths of the NIR spectroscopy method can only penetrate up to about 5 mm into the sample to be measured. The method is therefore sensitive to surface moisture. NIR spectroscopy method is suitable for use on conveyor belts as the method is fast and the measurement depth is small. The NIR method is affected by the temperature of the sample and its moisture content. These factors should be considered and the NIR spectroscopy sensors should be calibrated accordingly. The NIR spectroscopy method is suitable for a moisture content range between 34 – 72 %. A maximum standard deviation of 3.5% is obtained between the measured value of the NIR spectroscopy method and the value from the reference method (drying oven). NIR sensors can also be used to measure other parameters like the ash content or energy content in tandem with the moisture content measurement and this is a major advantage. However, the NIR spectroscopy method is still an expensive choice due to its high installation and maintenance costs [35, 39].

Microwave Spectroscopy

Microwave spectroscopy is based on the same principle as other spectroscopy methods, but it uses electromagnetic radiation in the microwave spectrum between 1 mm to 30 cm. Wood samples with moisture content can be considered as capacitors which have electrical conductors and are separated by insulating material [35, 41]. When an electrical voltage is applied on the wet biomass chips, a charge difference is produced. The ratio of the magnitude of electric charge stored to the voltage across the wood samples is called capacitance. The ratio between the capacitance obtained with the moist wood samples and the capacitance that would have been obtained in a vacuum is the dielectric constant. Wood samples with varying moisture content have different dielectric constant and the dielectric constant reveals how incident radiation on the wood samples would be affected. The radiation illuminated on a wood sample exhibits three major properties when it hits the material. Firstly, the propagation speed changes, and thus its wavelength depending on the dielectric constant of the material. Also, the polarization of the electromagnetic path is affected. In addition, the intensity of the radiation is reduced because the water molecules in the sample absorb energy and begin to rotate. Microwave spectroscopy measurements can be performed with an antenna that is in contact with the sample or an antenna that is a little distance away from the sample [35].

Microwave spectroscopy is affected by temperature because the method functions based on changes in the dielectric properties in the biomass sample and these dielectric properties are affected by temperature. When the sample is frozen, the water molecules will not be so free to move in the material and this affects its dielectric properties. The dielectric constant of ice is one-twentieth that of water and therefore measurements below the freezing point can be problematic [35].

The microwave spectroscopy method works based on the significant effect that water has on microwaves as compared to wood when measuring moisture content in wood chips. However, this also means that the changes in the waves will be small when the moisture content is low. At low moisture content levels, the measurements produce greater noise and become less reliable. However, tests have shown that it is useful for moisture content measurement between 7 – 50 % [35]. The microwave spectroscopy method reaches approximately 15 cm into the material to be measured and this is a major advantage over the NIR (Near-Infrared) method which only reaches a depth of about 5 mm into the material. The method is suitable for use on conveyor belts or stoker screws and does not need the sensor to be in contact with the material. The performance of this method can also be improved if more wavelengths are used [35, 43].

Nuclear Magnetic Resonance (NMR)

Nuclear magnetic resonance method for determining moisture content is based on the fact that hydrogen atom’s spin makes it a small magnet. When the sample is exposed to an external magnetic field, the hydrogen atom aligns itself in the direction of the field with a rotational motion that depends on the strength of the magnetic field [50].

There are two main techniques for measuring moisture content in samples using NMR. The first exposes the sample to an electromagnetic field with a fixed frequency. In addition, the sample is exposed to a magnetic field that is slowly varied in strength. At certain combinations of frequency and field strength, the hydrogen atoms will absorb some of the supplied energy [50]. By studying the absorption for different strengths of the magnetic field, one can infer the amount of hydrogen atoms and thereby the moisture content of the sample [37].

The second method for measuring moisture content using NMR is more precise [40]. It works by exposing a sample already in a magnetic field to a short and strong electromagnetic field perpendicular to the first field. An induced electric field is then generated that produces a voltage in a receiver coil wound around the sample. Mathematical processing of the signal results in an NMR spectrum provides information on the hydrogen atoms in the sample and thereby the moisture content. A higher moisture content in the sample produces a higher voltage in the coil often called Free Induction Decay (FID) [40]. The increase in the amplitude of the FID has been proved to increase linearly with moisture content [40].

The use of NMR to measure moisture content in the range of 0 – 60 % has been carried out at the Lawrence Berkeley National Laboratory in the USA and the results obtained were in agreement with the drying oven method [51]. The NMR method can also distinguish between water, ice, and wood. However, the signal generated from the ice does not increase linearly with the ice content, like the signal increases with the moisture content of water (liquid). Hence it is difficult to measure the ice content in wood chips [40].

X-Ray and Gamma Spectroscopy

X-ray spectroscopy is the illumination of the sample to be measured with radiation of wavelengths between 0.06 – 125 nm. Since different substances, like water and wood absorb different wavelengths to varying degrees, radiation with a minimum of two different wavelengths can be used to measure the moisture content in biomass samples. A transmitter is placed on one side of the sample to send out X-rays while a receiver on the other side measures how much of the different wavelengths passed through the sample. The X-ray spectroscopy shows good reproducibility, accuracy and precision when compared with the drying oven method in the moisture content range of 24 – 59 % [38]. The X-ray spectroscopy is independent of external factors like temperature or the degree of decomposition of the material because the radiation takes place inside the atoms. X-ray spectroscopy method is fast and has good penetrating power. It can be used to measure large samples and for measurements on conveyor belts. The deviation between the X-ray spectroscopy method and measurements with the drying oven is very low and the X-ray spectroscopy seems to be as good as several other methods used today [38].

Gamma radiation, like X-rays, is high-frequency radiation that affects the individual atoms rather than the bonds between them [37]. However, both X-ray and Gamma spectroscopy require certain safety measures to be taken because the radiation is dangerous for humans [37].

Radio Frequency Spectroscopy

Radio frequency spectroscopy is the illumination of the sample with radiation of wavelengths between 0.3 m and 10,000 m. The wavelength and propagation speed of the radiation will be affected depending on the dielectric constant of the sample material. In radiofrequency spectroscopy, you can place the transmitter and receiver on either side of the sample to be tested or an antenna could be used that functions as both a transmitter and receiver. The time delay of the radiation as it passes through the sample, or the attenuation of the signal are measured to determine the dielectric properties of the sample material, and this is a measure of the moisture content of the biomass sample [35].

An advantage of the radiofrequency method over the Near Infrared (NIR) Spectroscopy method is that it reaches further down into the sample. The radio frequency method is suitable for a wide moisture content range between 30 – 72 %. A maximum standard deviation of 2.7 % is obtained between the measured value of the radiofrequency spectroscopy method and the value from the reference method (drying oven) [35, 42].

Radio frequency spectroscopy method is more appropriate for performing measurements in containers because of its large measuring depth. It is less suitable for measurements on conveyor belts or stoker screws because it requires a distance of at least 0.5m between the transmitter and the receiver [35].

2.7.2.4 Electrical Methods

Conductivity / Resistance Method

The resistance moisture method is based on the fact that the electrical resistance of biomass or wood chips changes as the moisture level changes. Direct or alternating current is applied to the sample and the resistance or impedance is measured [35]. Dry wood has a very high resistance, but it decreases significantly if just a little moisture is gained such that the resistance of wood at a moisture content of 7 % is one millionth of the resistance of the dry wood. As more moisture is gained, the resistance decreases quite slowly until the fiber saturation point when the decrease in resistance almost stops. The fiber saturation point for wood is about 23 % moisture content. Above the fiber saturation point, the accuracy of the measurement is significantly lower than below the fiber saturation point. This is because for lower moisture contents, the transport of charges occurs through ions in the cell walls of the wood but when the fiber saturation point is exceeded, the transport of charges takes place through the free water, thus making the resistance measurement dependent on the ion content of water. The measurements performed by the resistance method above the fiber saturation point can deviate from the real value by up to 25 % [35]. Also, the uncertainty in measurements at low moisture content levels increases due to the very high resistance. The US Department of Agriculture also recommends that the resistance meters are not used except at a moisture content range of 7-23 % [52].

Apart from the moisture content range, the temperature of the sample being measured plays a major role in the accuracy of the measurement. The resistance of wood decreases at higher temperatures because the number of free ions that transport charges increase with the rise in temperature. Also, at temperatures below 0 ˚C when the water in the wood chips is completely frozen into ice, the measurement with the resistance method becomes inaccurate because the resistance of frozen wood is many times higher than normal [39]. Resistance method moisture meters must therefore be calibrated for different temperature ranges. Other factors that affect the measurement of the resistance method moisture sensors are impurities like chemicals or salt water in the sample [35].

Capacitance Method

A capacitor is made up of two electrical conductors that are separated by an insulator. When an electrical voltage is applied across the conductors, a charge difference occurs between the two sides of the capacitor. The relationship between the voltage applied and the charge difference is called capacitance [35, 53].

Using a different insulating material between the two conductors will result in a different capacitance. The ratio between the capacitance measured with a selected insulating material and the capacitance when vacuum is used as the insulation is called the dielectric constant. Dielectric constant in wood varies with the moisture content. The moisture content in wood can be obtained by measuring the capacitance of the wood sample. This is because measuring the capacitance of the wood gives a measure of the dielectric constant and thus the moisture content in the wood [35].

The dielectric constant increases with increase in temperature and is also dependent on the frequency of the alternating voltage. Capacitance moisture sensors can measure low moisture contents in wood samples, but the accuracy is lower. The sensors can also measure high moisture contents but the rate of change in the dielectric constant is higher when the moisture content is above the fiber saturation point. Above the fiber saturation point, the increase in the dielectric constant is linear. It is recommended that the capacitance moisture sensors are not used for moisture content higher than 30% as they produce greater errors at higher moisture content [53].

The suitability of moisture measurement methods for a particular process is based on the requirements of the process. In order to select a moisture measuring method in the design of a process control system, it is important to have an understanding of the requirements of the process [35].

2.8 Scientific Contribution

The literature study was performed to have an overview of biomass, heating systems, and moisture measurement methods. The study revealed the gap in current research due to lack of information on the relationship between varying moisture content in biomass wood chips and the overall efficiency of biomass heating systems. This research also built on existing knowledge using SIPOC tools and PID control loop to provide a better understanding of heating systems. Moisture measuring techniques from existing literature were also identified and categorized based on their mode of operation [30, 32].

The following chapters in this research will seek to design a process control system for combustion regulation by the measured moisture content in the biomass wood chips. The process control system would regulate other factors in the combustion process in order to increase the overall efficiency of the biomass combustion system and the effective heat exchange. A control system design process would be useful in the design of a process control system.

3 Methodology

This chapter is focused on the design of the process control system for the regulation of the combustion process by measured moisture content in the biomass wood chips. For the process control design a control system design process would be used. Lean Six Sigma tools will also be used for the process design and modelling and experiments would be performed [54, 55].

3.1 Control System Design

The design of any process may progress in different directions before the desired outcome is obtained. It is a well-reasoned process through which a goal is achieved in response to a perceived need while managing defined constraints. The design process is an iterative, innovative, and nonlinear process. The best method for performing the most effective engineering design is parameter analysis and optimization. Parameter analysis is based on [55]:

1. Identification of the main parameters
2. Development of system configuration
3. Evaluation of the system configuration's ability to meet the design needs.

These three steps in parameter analysis are iterative and the parameters can be optimized after they are identified, and the configuration is developed.

A control system design is a type of engineering design with the goal of obtaining the system configuration, specifications and identifying the major parameters of the proposed system to meet a desired need. The control system design process as shown in Figure 6 is made up of seven major blocks that can be categorized into three groups [55]:

1. Establishment of goals and control variables and definition of specifications against which performance is compared.
2. Defining and modelling of the system.
3. Control system design, simulation, and analysis.

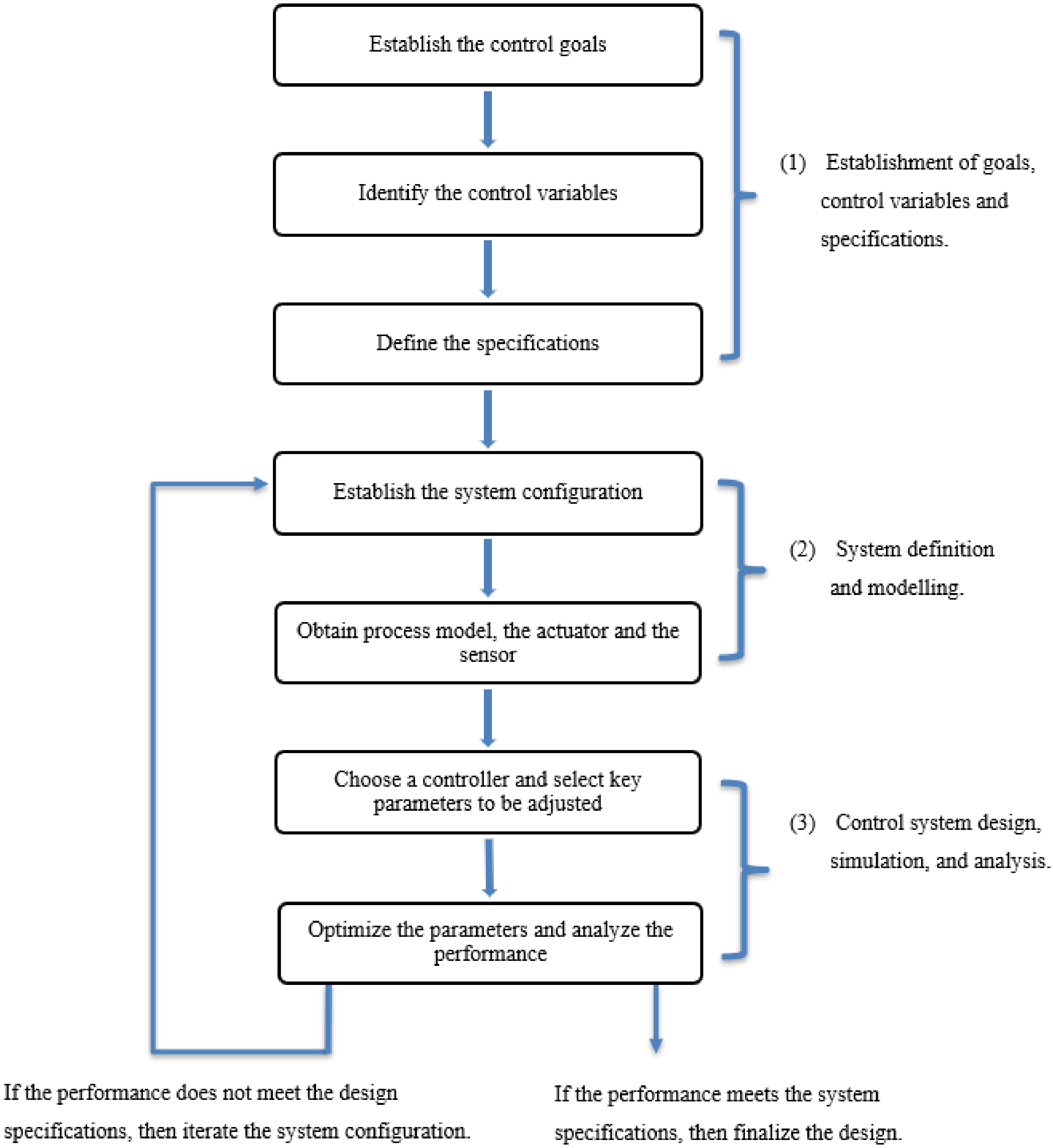

Figure 6. The control system design process [55].

The first stage in the control system design process is the establishment of control goals. The main goal of this project is to optimize the overall biomass combustion system efficiency and the effective heat exchange at the heat exchanger. The second stage is to identify the variables that are to be controlled. The variables that are vital for an efficient combustion process given the variation in the moisture content of the biomass wood chips are the feed rate of the wood chips in the feeding system, the movement of wood chips through the combustion chamber and the air supply rate. The third stage is to define the specifications of the system especially as it relates to the expected accuracy [55]. The system specification will detail how the system should perform and would usually consider the systems regulation against disturbances, response to commands, generation of realistic actuator signals. The system must then be configured to achieve the desired performance. A typical system configuration will consist of a sensor, controller, and actuator connected to the process under control [55]. The desired accuracy will be an important criterion in the selection of the sensor, controller, and actuator to be used. The controller is the combination of the comparison element and the control law implementation element which compares the desired response of the system to the actual response and forwards the error signal to the actuator in order to modify the inputs. The final stage in the control system design process is the adjustment of the system parameters to achieve the expected performance. If the performance of the system meets the specification, then the design can be finalized, and the results can be documented. Otherwise, the system configuration could be improved through the selection of improved sensors and actuators and the design steps repeated until we can meet the desired specifications [55].

3.1.1 Established Goals, Control Variables and Specifications

3.1.1.1 Goal

The aim of this project is to improve the combustion efficiency in the biomass furnace (KSM multistoker) and increase the heat transfer performance at the heat exchanger. Figure 7 is a schematic of the KSM Multistoker XXL that identifies some parts and processes that occur.

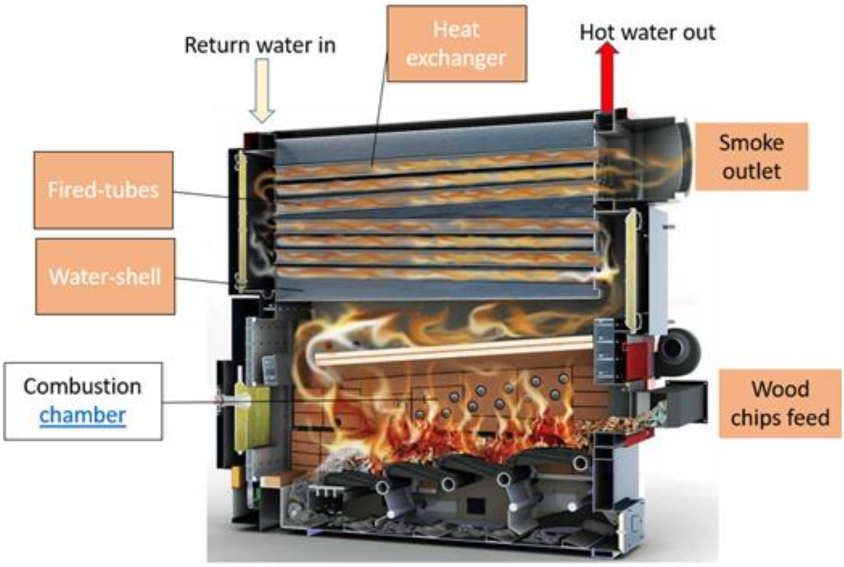

Figure 7. System overview of the KSM Multistoker XXL

3.1.1.2 Control Variables

1. The air supply rate for combustion (fan speed)

   The KSM-Multistoker XXL has its primary air inlets below the fireplace and the secondary air nozzles mounted at the sides of the KSM-Multistoker XXL as shown in Figure 8. The KSM-Multistoker XXL has up to 6 fans, and they can be controlled independently. All the fans receive air intake from the bottom part of the boiler to cool down the bottom section of the boiler and also supply preheated air to the combustion, and this is vital when burning fuel with high water content. If the biomass wood chips are wet, the air is to be supplied directly into the flame from the primary air inlet but if the biomass wood chips are dry the secondary air must be supplied above the flame so it can mix with the gases. Therefore, to control the combustion in the best way it is important to regulate the air supply into the combustion chamber depending on the moisture content of the biomass wood chips.

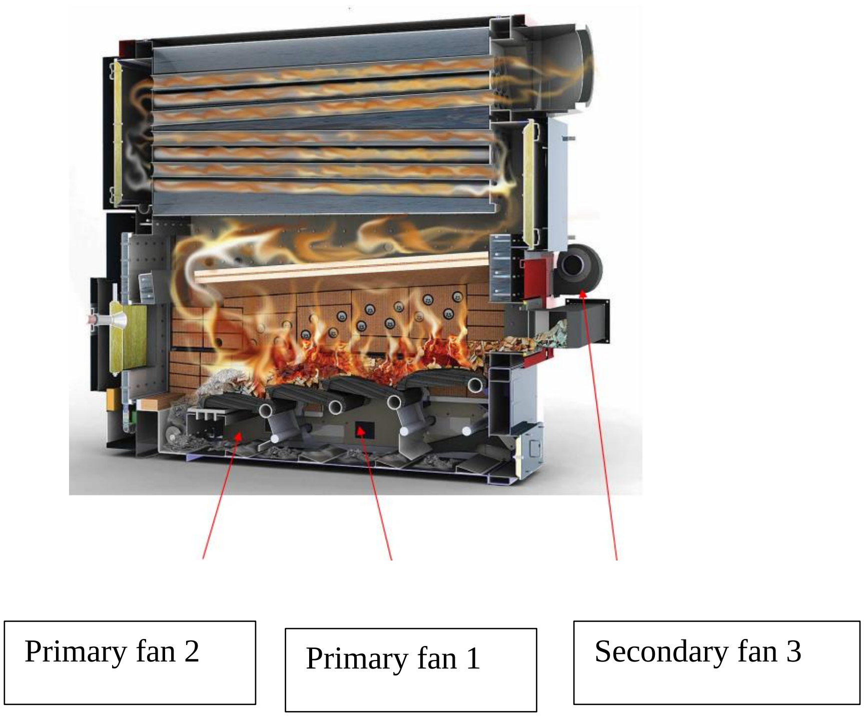

Figure 8. Air supply system for the KSM Multistoker XXL

2. The feed rate of the biomass wood chips in the feeding system (stoker screw speed)
   The KSM-Multistoker XXL can burn different types of biomass wood chips, but the efficiency of combustion varies based on the moisture content. If the moisture content in the wood chips is very high and the combustion chamber is overfilled, the fire can be quenched. The KSM-Multistoker XXL has a feeding system that is made up of stoker screws. If the stoker screws run quickly then the combustion chamber is overfilled, and the fire can be quenched. However, if it moves too slowly then fuel is lacking to support burning in the combustion chamber. Thus, it is important to be able to regulate the speed of the stoker screws depending on the moisture content of the biomass wood chips. A 3D drawing of the stoker screw is shown in Figure 9.

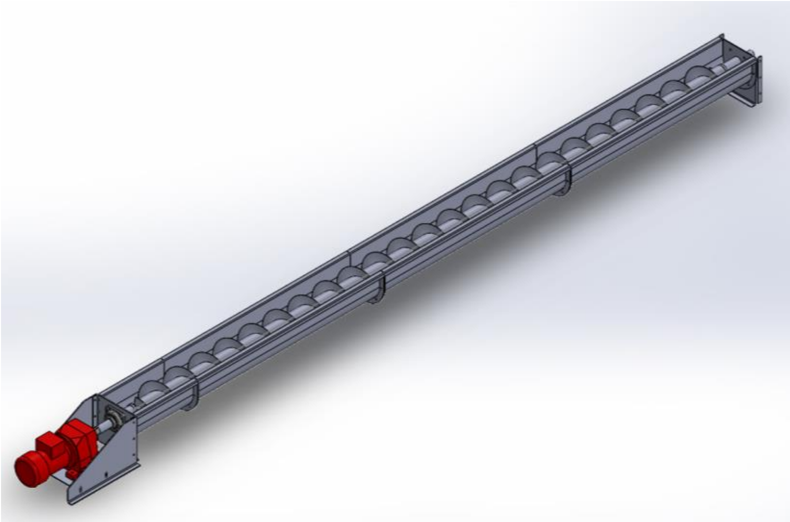

Figure 9. 3D drawing of the stoker screw.

3. Speed of moving floor

   The KSM-Multistoker XXL has a moving floor that moves the fuel forward in the combustion chamber. If the biomass wood chips have high moisture content and the moving floor moves too slowly there is a risk that the combustion chamber can be overfilled, and the fire will be quenched. However, if the moving floor moves too quickly, then the fuel is not burned properly before it exits the combustion chamber. Hence, it is important to be able to regulate the speed of the moving floor in the combustion chamber depending on the biomass moisture content. Figure 10 shows biomass wood chips on the moving floor in the combustion chamber.

Figure 10. Biomass wood chips on the moving floor

3.1.1.3 Specifications

Specifications in control system design are descriptions that clearly state how a system or device should perform. This could be in terms of the accuracy that is to be achieved. The required accuracy will then be a determinant factor in the selection of the sensor to measure the controlled variable. A process diagram for the KSM Multistoker XXL with temperature measurements at different stages of the process is shown in Figure 11.

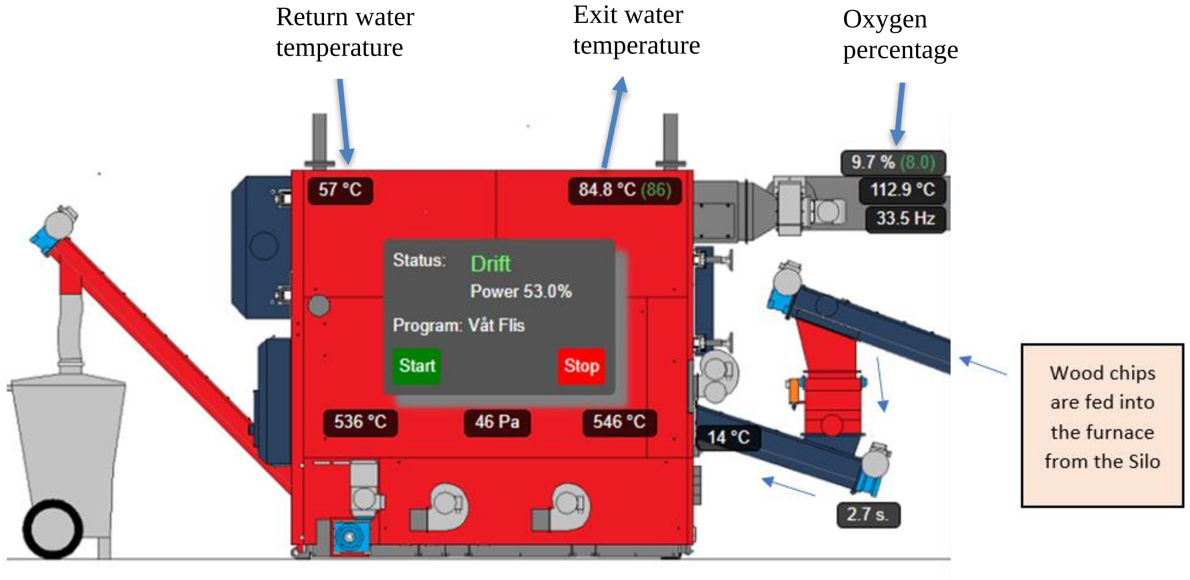

Figure 11. A process diagram for the KSM Multistoker XXL

A questionnaire was also administered to the system owners to obtain system specifications that would help in the design of the process control system for combustion regulation by moisture content measurement in the biomass feed. The details of the questionnaire and the corresponding feedback are provided in Table 3.

Table 3. Administered questionnaire to Dragefossen to obtain specifications.

Question	Feedback
Material	
Description	Biomass wood chips made from a mixture of spruce, pine, or birch trees.
Particle size:	average of 60 mm ± 20 mm
Process	
Process description	Combustion process
Process location for sensor installation	Just before the combustion chamber, as close to the furnace as possible
Any special requirements	None
Required sensor sigma:	0.83
Temperature	
Moisture range of material	20 % - 50 %
Temperature range of material	-5 ˚C – 35 ˚C
Temperature range of ambient air	10 ˚C – 35 ˚C
Flow rate	
Material flow rate	-
Is flow rate constant:	Constant when running.
Is material flow continuous or batched	Batched.
Biomass furnace	
Will the sensor control the furnace	Yes
Type of furnace:	Biomass furnace
Manufacturer of furnace	KSM-Stoker Denmark
Others	
Diameter of the screw conveyor	350 mm
Will the screw conveyor be full of wood chips	Yes

3.1.2 System Definition and Modelling

A control system is the interconnection of components to form a system that will produce a desired system response. A signal error could then be generated if there is a variation between the desired system response and the actual system response. The signal is then used to control the results of the process working in a closed-loop sequence. The closed-loop sequence otherwise known as a feedback system is shown in Figure 12.

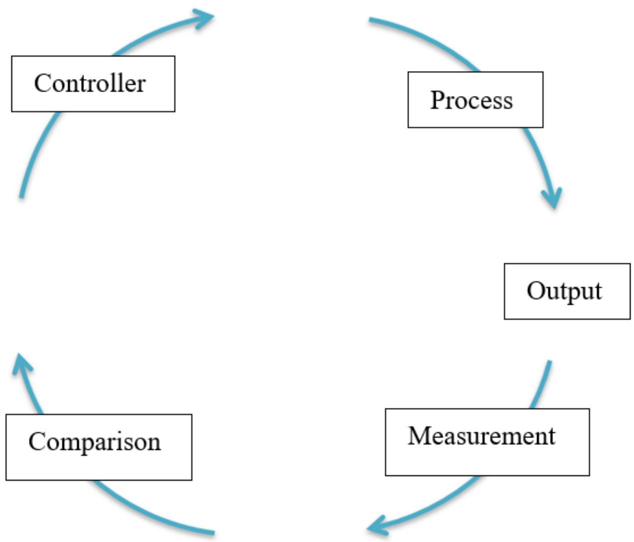

Figure 12. A closed-loop feedback system

A closed loop system compares the measured output signal with the desired output to generate an error signal that is fed into the controller to regulate the actuator. Closed-loop systems can be complex and expensive, but they are very useful in decreasing the sensitivity of the systems to variations in the process parameters. In open-loop systems, errors and variations result in an inaccurate output but a closed-loop system observes the inaccurate output due to variation in process parameters and it attempts to correct the inaccurate output.

In this process control design, a closed-loop feedback control is utilized to improve the system performance. A closed-loop feedback system for combustion regulation by moisture content in biomass feed is illustrated in Figure 13.

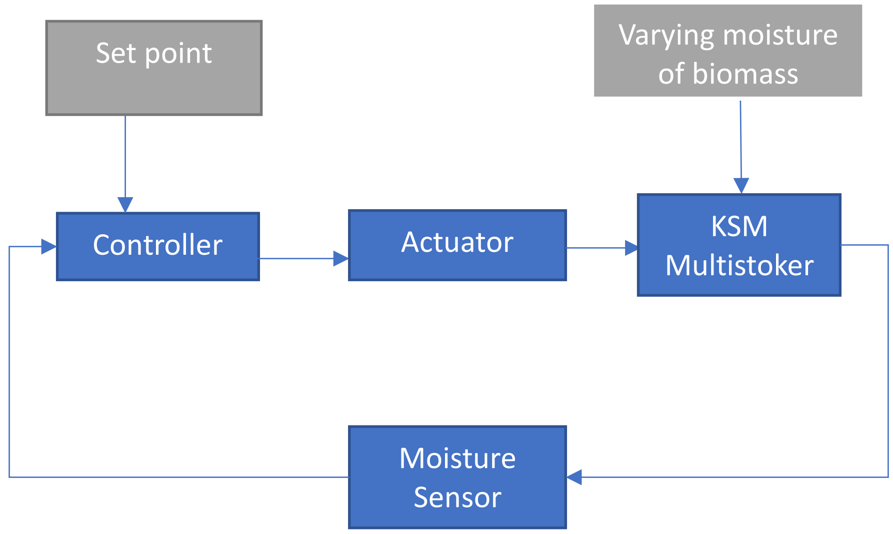

Figure 13. Closed loop control system with moisture sensor for combustion regulation.

The proposed system configuration consists of a moisture sensor, the process, the actuator, and the controller which in this project is a PID controller. However, based on the three control variables established, different system configurations must be defined.

The system configuration for controlling the fan speed consists of the moisture sensor, the PID controller and the fan motor which regulates the air flow into the combustion furnace. Figure 14 shows the system configuration for air supply regulation.

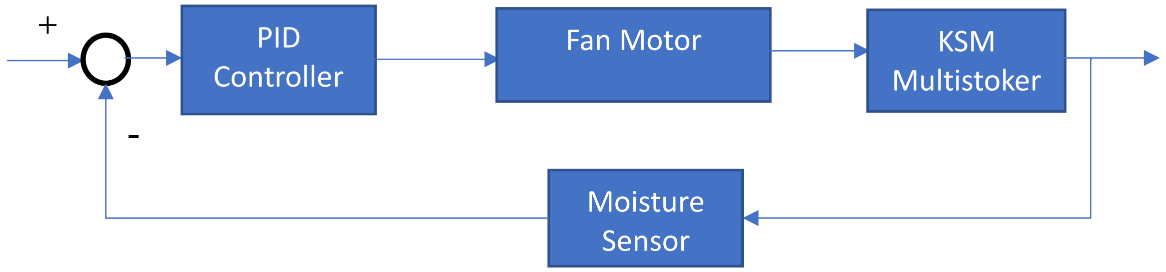

Figure 14. Control system for regulating air supply into the combustion chamber.

The system configuration for the control of the stoker screw speed is shown in Figure 15. It consists of the moisture sensor, the PID controller and the stoker screw motor which adjusts the feed rate of the biomass wood chips into the furnace.

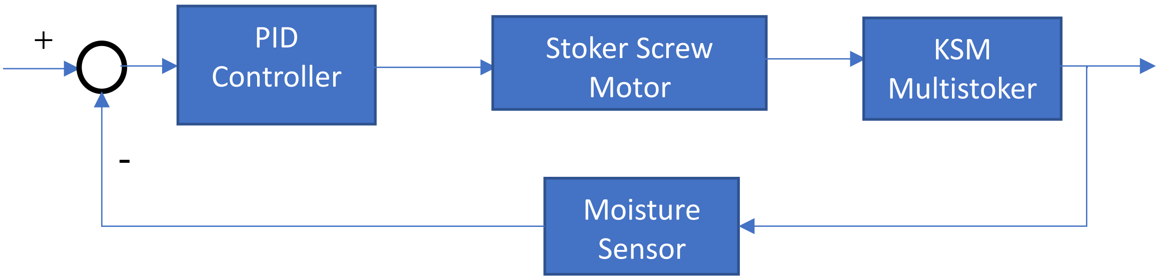

Figure 15. Control system for regulating the feed rate of biomass wood chips in the feeding system.

The system configuration for controlling the movement of biomass wood chips through the combustion chamber is shown in Figure 16. It consists of the moisture sensor, the PID controller and the moving floor motor which regulates the movement of the biomass wood chips through the combustion furnace.

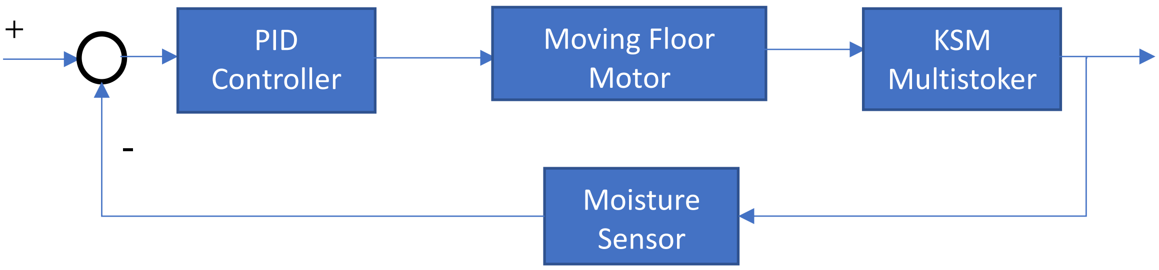

Figure 16. Control system for regulating the feed rate of biomass wood chips in the combustion furnace.

Identifying the actuator for the system depends on the process, but the method of actuation must be able to effectively adjust the process performance. Also, the moisture sensor must have the capability to accurately measure the moisture in the biomass wood chips and send a signal to the PID controller which modulates the actuator.

3.1.2.1 Criteria for Selection of Moisture Sensors

Several methods for measuring moisture content in a variety of materials have been identified and discussed. The two electrical methods based on resistive and capacitive measurements and the spectroscopic methods based on electromagnetic radiation are the most suitable methods in the measurement of continuously flowing biomass wood chips due to their mode of operation and the speed at which measurement can be performed. However, some of the moisture measurement methods like the Karl Fischer method or the phosphorus pentoxide method are not suitable for measuring the moisture content in biomass wood chips due its mode of operation and the properties and nature of the wood chips. Some other methods are not ideal for continuous measurement of moisture content in biomass wood chips as the wood chips are conveyed from silos or storage areas to the furnace for combustion.

Although capable of continuous measurement of moisture content in biomass wood chips, these electrical and spectroscopic methods each have their own unique strengths and weaknesses. The electrical and spectroscopic methods measure properties in the wood chips that are affected by changes in the moisture content. Therefore, these methods are based on the properties that can both be detected and that differ between wood and water. However, usually the measured properties are affected by other properties of the wood, and this greatly influences the effectiveness of the moisture sensor. One factor that greatly influences the measurement of moisture content in wood chips by the measuring sensors is the fiber saturation point. At approximately 23 % moisture content, the fiber saturation point is reached. Above the fiber saturation point, the water molecules are loosely bound to the wood than below the fiber saturation point and these affects the wood and dielectric properties [50]. Another factor that influences the measurement results obtained is the temperature. This is because the properties of water and wood are affected by temperature. Above the freezing point of water, temperature has a little influence on the properties of water and wood but below the freezing point when water has turned to ice, the properties are greatly changed. This happens because the molecules become more closely bound together and have less opportunity to move thus affecting both the mechanical and electrical properties. Several other factors like the density of the wood chips being measured and the presence of impurities and chemicals also affect the accuracy of the measurement of moisture content in wood chips. Also, beyond the influence of wood and water properties by other factors, the different measuring methods have their own inherent limitations and benefits. For instance, the different moisture sensors have varying measuring depth, accuracy, calibration requirements and cost. It is therefore important to evaluate the properties of the wood chips to be measured in order to find the best type of moisture sensors to be used. Table 4 shows a comparison of some of the relevant properties and performance characteristics of three spectroscopic methods and the two electrical methods.

Table 4. Relevant properties and performance characteristics of spectroscopic and electrical moisture sensors.

Factors	**NMR**	**NIR**	**Microwave**	**Conductometry/ Resistance**	**Capacitance**
Temperature	Problematic at T < 0 ˚C	Calibration required to measure T < 0 ˚C	Calibration required to measure T < 0 ˚C	Problematic at T < 0˚C	Dielectric constant increases with increased temperature
Density	-	Depends on density	Depends on density	-	Affects dielectric properties
Measuring Depth	-	Surface measurement (up to 5 mm)	Up to 15 cm	-	-
Impurities and Chemicals	Not affected	Affect measurement	Not affected	Affect measurement	Affect measurement
Accuracy above fibre saturation point (23%)	High accuracy between 0 – 60 % (Most accurate)	High accuracy between 34 – 72 % (Less accurate than NMR)	High accuracy between 7 – 50 % (less accurate than NIR)	Accuracy affected by as much as 25 %	Not to be used above 30% moisture content
Accuracy Below Fibre Saturation Point	Recommended	Not recommended below 34 %	Suitable	Deviate less than 2%	Lower accuracy for lower moisture content.
Speed	In seconds	In seconds	In seconds	In seconds	In seconds
Recommendation	Use between 0 – 60 %	Use between 34 – 72 %	Use between 7 – 50 %	Use only between 7 – 23 % moisture level	Lower accuracy than Resistance meters
Calibration and Maintenance Costs	Very high	High	Medium	-	-
Installation Costs	Extremely expensive (from ten to hundred thousand dollars	Very expensive (tens of thousands of dollars)	A few thousand dollars	-	-
Safety	Safe	Safe	Safe	Safe	Safe

The resistance and capacitance sensors are limited because of their operating technology which is easily affected by impurities, chemicals, and temperature. It can also be observed from the table above that these methods have low performance above the fiber saturation point (23%) and according to the specification provided by the process owners, we expect the water content to range from 20 – 50 %.
After comparing the different types of moisture sensors available for the measurement process, it can be observed that the NIR sensors have high installation and maintenance costs. Also, the NIR sensors only provide surface measurements of up to 5 mm which is unsuitable for the biomass combustion system which feeds a great quantity of biomass wood chips continuously.

The NMR sensors have very high installation and maintenance costs and although they provide very accurate measurements, they are most suitable for measuring moisture contents for a large volume of space and not smaller ducts.

The microwave moisture sensors fit the specified moisture content range of wood chips which is between 20 – 50 %. They also have the lowest installation and maintenance costs when compared to the NMR and NIR which all have similar accuracy levels.

Therefore, the most suitable moisture measurement sensor for the process control system defined in this project is the microwave moisture sensor. This was determined after considering various factors like the moisture content range, depth of measurement, accuracy, and cost.

3.2 Technical Solutions for Installation of Microwave Moisture Sensor in the KSM Multistoker XXL

The microwave moisture sensors can be installed or used at various stages in the process of feeding woodchips until they are burned in the biomass furnace. These locations can include the installation of the moisture sensors in the wood chips feeding system close to the storage site, a long way before the wood chips arrive at the KSM Multistoker XXL or the installation of the moisture sensors close to the combustion chamber just before the wood chips enter the furnace. The microwave moisture sensors can be installed anywhere between the storage area and the KSM Multistoker XXL as shown in Figure 17.

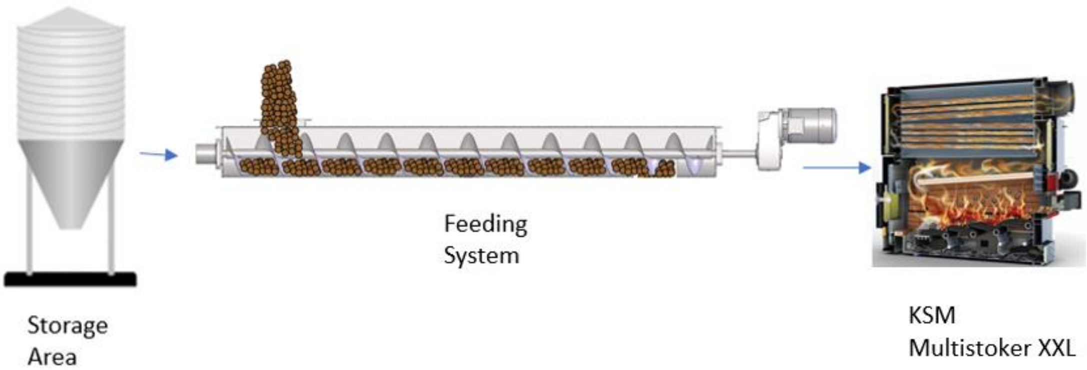

Figure 17. Process flow from the storage area to the KSM Multistoker XXL

However, in this project, based on the specification provided by the system owners, the sensors should be installed as close to the furnace as possible in the feeding system. This specification was given in order to have better control of the process. The KSM Multistoker XXL with the feeding system (stoker screws) is shown in Figure 18. As the biomass wood chips proceed towards the furnace to be burned, the temperature increases, and the wood chips lose some of its moisture content. Moisture measurements are dependent on temperature, and it is better for all the ice in the wood chips to melt before they are measured. Hence, to have accurate moisture readings that would be useful in controlling parameters in the furnace, it is important to have the moisture content measured close to the entrance into the furnace.

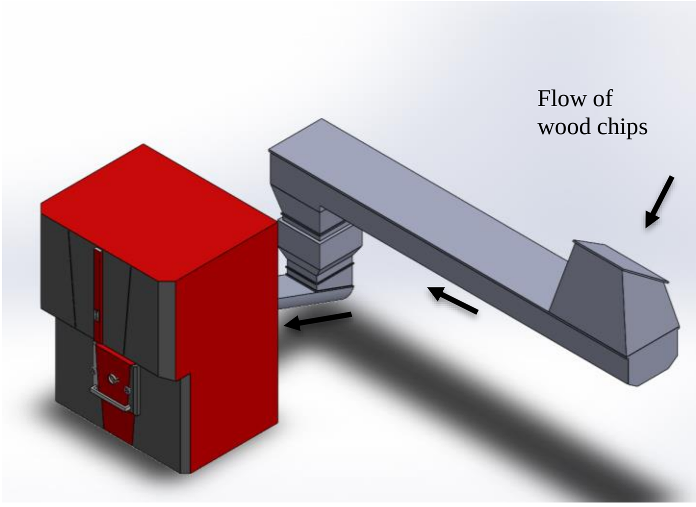

Figure 18. 3D drawing of KSM Multistoker XXL with feeding system.

3.2.1 Microwave Moisture Sensor

The microwave moisture sensor suitable for the KSM Multistoker XXL should be flush and mounted along the feeding system. Since microwave moisture sensors can perform moisture measurements in seconds, they are ideal for continuous measurement of moisture in wood chips as they move along the feeding system. The selected sensor must be compatible with the other elements of the control system and must be capable of being calibrated. Figure 19 shows the 3D design of the selected microwave moisture sensor.

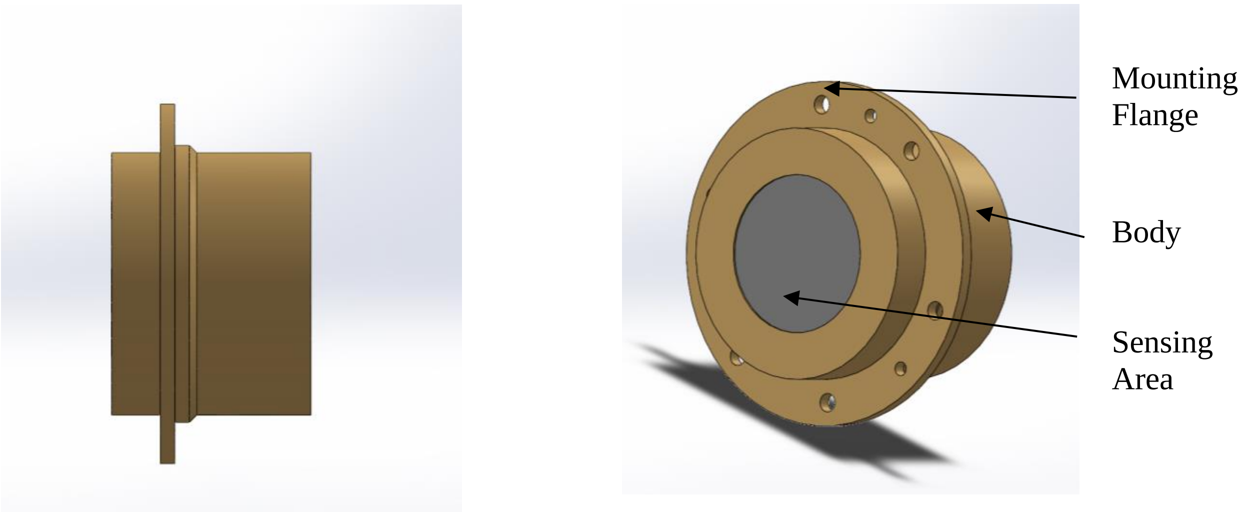

Figure 19. A 3D design of the microwave moisture sensor.

3.2.2 Moisture Sensor with Flowing Wood Chips

To obtain accurate moisture measurement, the microwave moisture sensor should be installed where the biomass wood chips will contact the face of the sensor at a controlled and consistent flow rate.

The following guidelines were considered for proper positioning of the microwave moisture sensor:

- The sensor should be located where the wood chip flows at a constant rate.
- If the sensor is installed on a curved surface, the sensing area of the microwave moisture sensor should flush with the internal wall.
- Avoid installing the microwave moisture sensor in an area of turbulent wood chip flow.
- Avoid installing the sensor where there is material build up on the sensing area.
- The sensor should be positioned where it is easily accessible for routine maintenance checks and adjustment.
- A sampling point should be close to the sensor for calibration purposes.
- The sensor should be positioned away from electrical interferences.

3.2.3 General Installation Advice

If the surface on which the sensor is to be installed is flat, then the sensor must flush with the internal surface as shown in Figure 20.

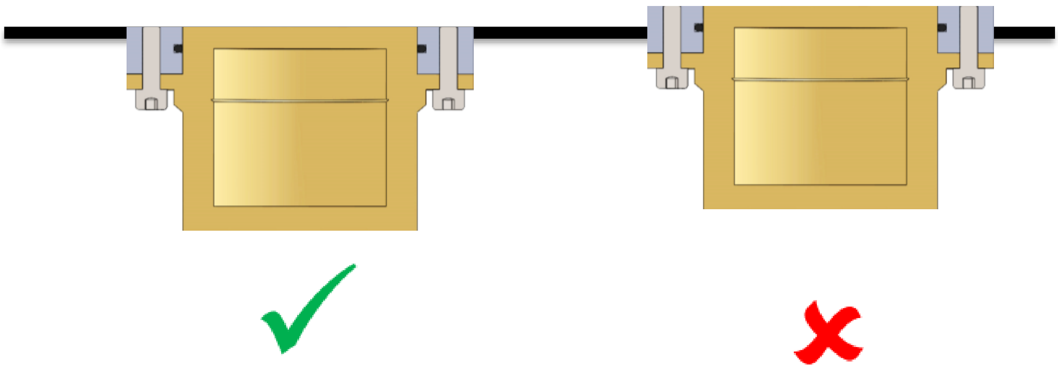

Figure 20. Installation of microwave moisture sensor on a flat surface.

If the suitable surface for installation of the sensor is curved, then the sensing area of the sensor must also flush with the radius of the internal wall as seen Figure 21. Installing the microwave moisture sensors on curved surfaces can pose certain restrictions due to the geometry of the parts. However, this can be dealt with using simple fabrication or mechanical methods.

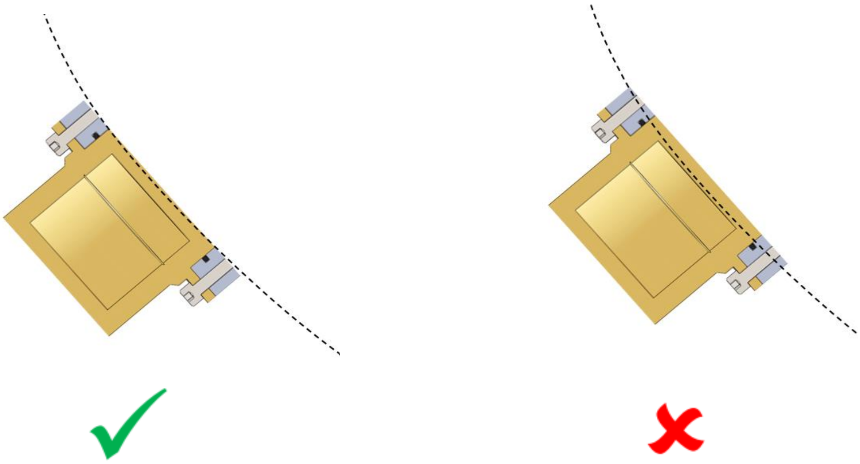

Figure 21. Installation of microwave moisture sensor on a curved surface.

3.2.4 Screw Conveyor / Stoker Screw

Based on the system configuration and the guidelines listed in section 3.2.2 it is recommended that the sensor is installed on the second screw conveyor shown in Figure 22. The second screw conveyor is preferred to the first screw conveyor for installation of the moisture sensor due to the backfire from the KSM Multistoker XXL during the combustion of biomass wood chips.

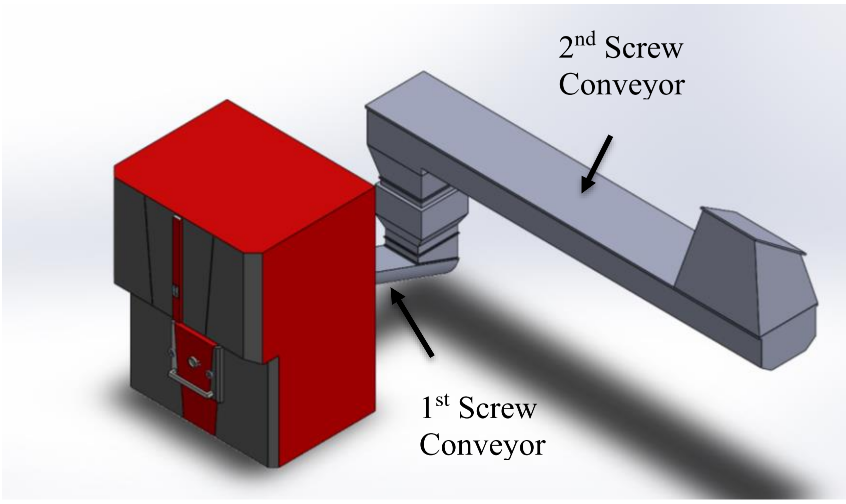

Figure 22. Stoker screws for the KSM Multistoker XXL.

Also, an experiment was performed to observe how materials flow through the screw conveyor, and it was noticed that materials always build up on one side of the screw conveyor. One of the relevant properties of microwave moisture sensors is the influence of density on the accuracy of moisture measurement and this underlines the importance of installing the sensor on the side of the screw conveyor with the buildup. The behavior of materials in the screw conveyor can be observed in Figure 23.

Figure 23. Experiment to show behavior of materials in a screw conveyor.

Due to the buildup of materials on one side of the screw, it is recommended that the sensor is installed at 30 ˚-45 ˚ above the base. Figure 24 shows the schematics for installation.

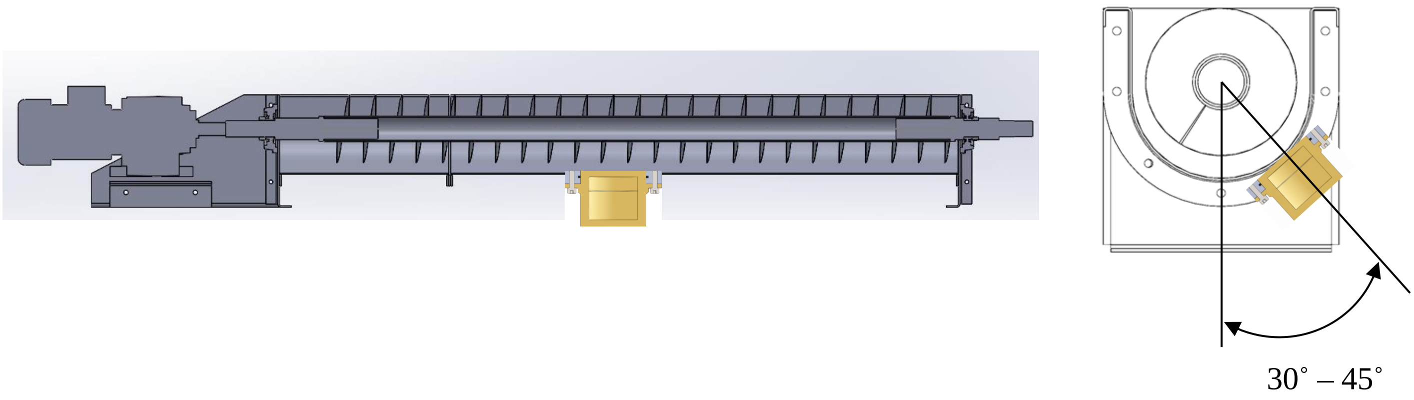

Figure 24. Schematic showing the angle of installation of the microwave moisture sensor.

It is also important for the sensor to be placed in such a way that the sensing area is continuously covered by a fixed density of biomass wood chips.

3.2.5 Installing the Microwave Moisture Sensor

The moisture sensor has a mounting flange that allows it to be connected to a fixing plate using screws, as it can be seen in Figure 25. The fixing plate is the part that is welded to the internal wall or floor of the stoker screw.

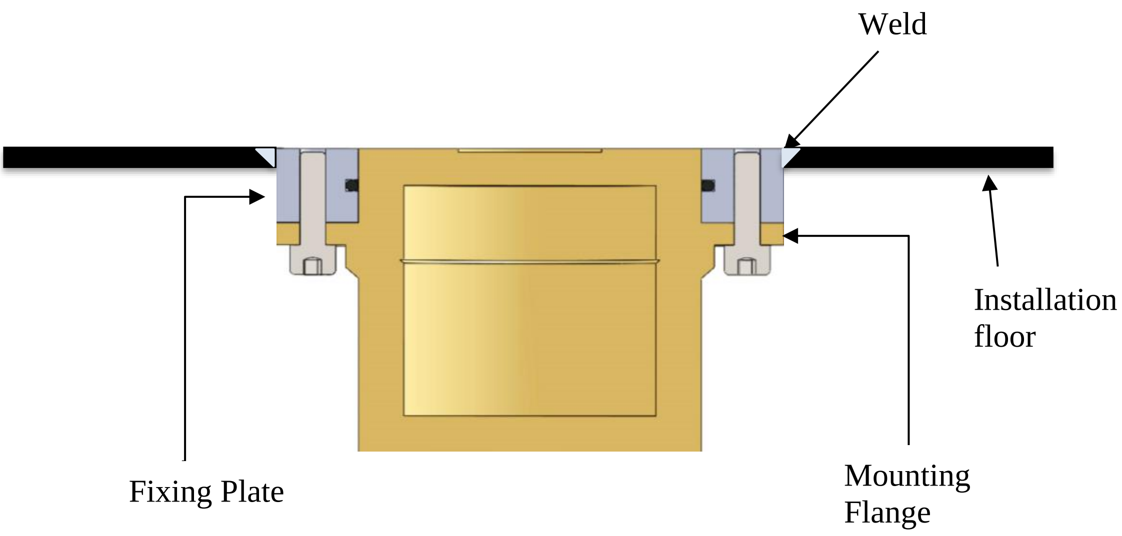

Figure 25. Microwave moisture sensor installation with fixing plate

3.2.5.1 Mounting the Fixing Plate

To ensure that the fixing plate is installed in a flush position with the internal wall of the stoker screw, it is necessary to cut a hole the size of the diameter of the fixing plate through the external and internal wall of the stoker screw.

The fixing plate can then be welded, either from inside or outside of the stoker screw. Only ensure the fixing plate is in a flush position with the internal wall and that the O-ring is greased and placed in the O-ring groove. Figure 26 shows the flush installation of the fixing plate and the internal wall of the stoker screw.

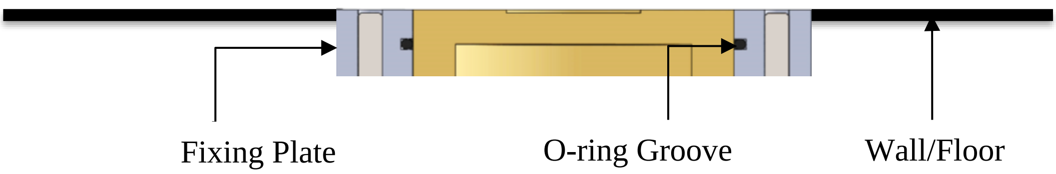

Figure 26. Fixing plate flush with flat surface

It is also important that the fixing plate should not be welded with the microwave moisture sensor attached because this can cause damage to the sensor.

3.2.5.2 Attaching the Sensor to the Fixing Plate

The microwave moisture sensor is inserted into the fixing plate and joined using six fixing screws. It must be confirmed that the sensing area of the moisture sensor also flushes with the internal wall of the stoker screw.

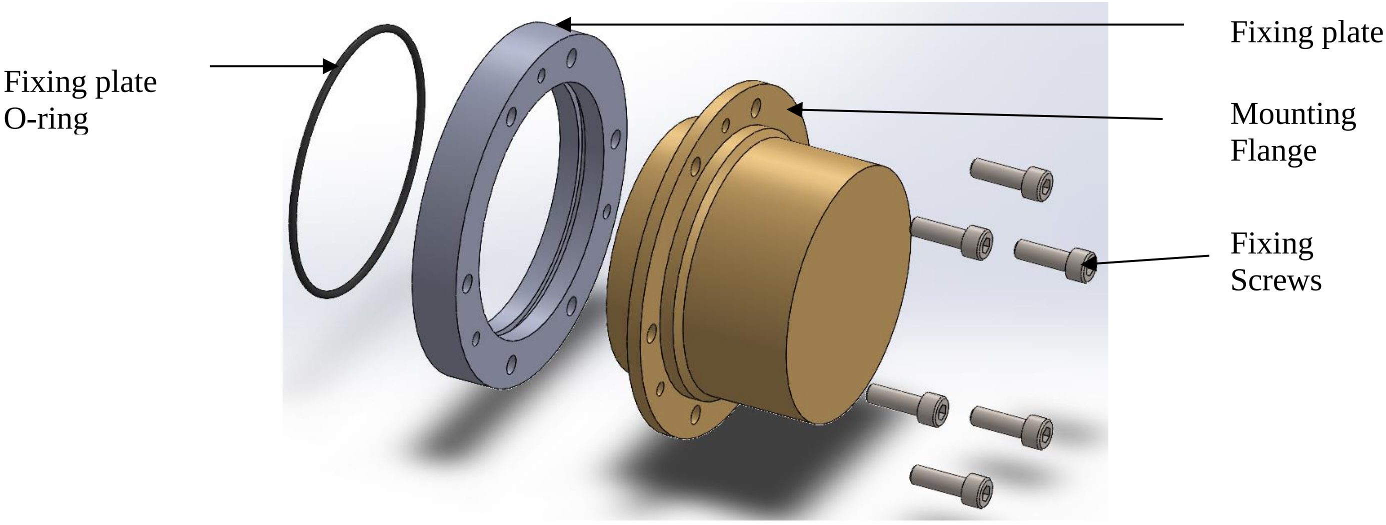

Figure 27. Exploded view of the assembled moisture sensor and fixing plate.

A proper installation will provide a good measure of the moisture content in the biomass wood chips and an understanding of the different variables that influence the moisture measurement process will further improve the accuracy. Therefore, it is important to also use Lean Six Sigma tools for process modelling and improvement.

3.3 Design and Modelling of the Moisture Measurement Process with Lean Six Sigma

Repeatability and reproducibility are two important terminologies used during moisture measurement of biomass wood chips. Repeatability is the ability of a measuring method to provide the exact result for the same sample material when tested under identical measurement conditions. Reproducibility is the ability of a measuring method to provide the exact result for the same sample material when tested under different measurement conditions [56]. Reproducibility and predictability are inversely related to variation. As variation increases, reproducibility and predictability decrease due to higher probability of nonconformity. Variations result due to design, material, process speed, process conditions and process layout. Likewise, process performance is a function of design, material, process speed, process conditions and process layout [57]. A process model for analyzing the factors responsible for variation in output moisture percentage provided by the sensor is shown in Figure 28.

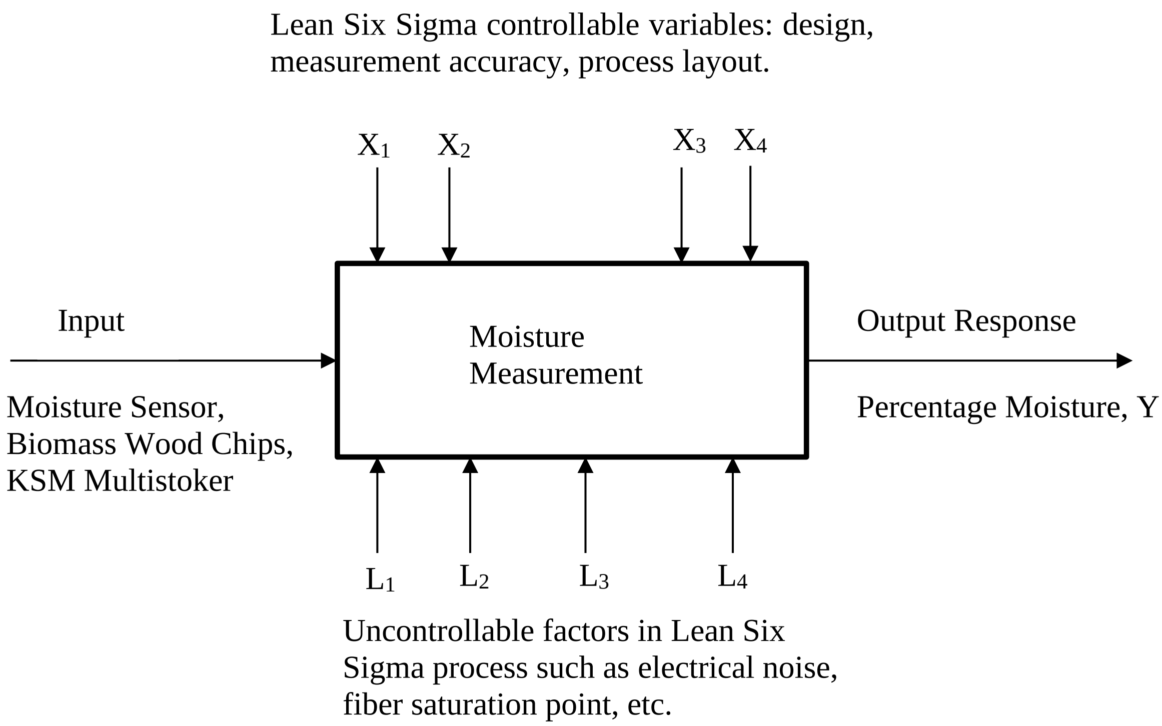

Figure 28. Model of a moisture measurement process

3.3.1 Mathematical Modelling of Lean Six Sigma Relations

Mathematically, the value of the dependent variable response Y changes with respect to the independent variables $x_1, x_2, x_3, \ldots, x_n$ of n number of factors such that

$$Y = f(x) = f(x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n) \qquad (12)$$

Where Y is the dependent variable, *f* is the response function, and x_i is the independent variable or cause. Considering the moisture measurement process with design, measurement accuracy and process layout as the controllable variables, the equation above becomes

$$Y = f(x_1, x_2, x_3) \qquad (13)$$

Y is the process (moisture measurement) performance and x_1, x_2, and x_3 each represent respectively the design, measurement accuracy and process layout of the moisture measuring system. However, when closely observing design, measurement accuracy and process layout, one would realize that these factors are dependent variables and so they depend on other variables.

Therefore, the equation above can be written as

$$Y = f(y_1, y_2, y_3) \qquad (14)$$

The equation above can be expanded into the equations below:

Design = *f* (dimensions, position of installation, etc.)

or

$$y_d = f(x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n) \qquad (15)$$

Measurement accuracy = *f* (temperature, density, flowrate, etc.)

or

$$y_{ma} = f(x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n) \qquad (16)$$

Process layout = *f* (distance from sampling point, space availability etc.)

or

$$y_{pl} = f(x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n) \qquad (17)$$

y_d, y_{ma} and y_{pl} are dependent variables and predicted responses for the independent variables x(s) which are called the independent causes of variation. The polynomial representation of the equations above at any point ($x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n$) in the factor space or n-dimensional space, can be given in the regression equation:

$$y_n = b_0 + b_1x_1 + b_2x_2 + \ldots + b_{11}x_1^2 + \ldots + b_{12}x_1x_2 + \ldots + b_{111}x_1^3 + \ldots \text{etc.} \qquad (18)$$

And in the summation notation form

$$y_n = b_0x_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{\substack{i=1 \\ i<j}}^{n-1} \sum_{j=2}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n-2} \sum_{\substack{j=2 \\ i<j<k}}^{n-1} \sum_{k=3}^{n} b_{ijk} x_i x_j x_k + \ldots \text{etc.} \qquad (19)$$

Where x_0 is a dummy variable and always equal to 1.

$x_1, x_2, x_3, \ldots, x_{n-2}, x_{n-1}, x_n$ are independent variables that affect the value of y.

b_0, b_i (i = 1, 2, . . ., n), b_{ij} (i = 1,2, . . . , n; j = 1, . . . , n), b_{ijk} (i = 1, 2, . . ., n; j = 1, . . . , n; k = 1, . . . , n), . . . etc. are unknown independent coefficients which can be estimated through experimental data or calculated using statistical software.

When dealing with three factors x_1, x_2 and x_3, the corresponding polynomial equation becomes

$y_n =$ $b_0 + b_1x_1 + b_2x_2 + b_3x_3$	Linear terms	
$+b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2$	Quadratic effects	
$+b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3$	Binary interaction effects	
$+b_{123}x_1x_2x_3 + b_{112}x_1^2x_2 + b_{113}x_1^2x_3$		(20)
$+b_{122}x_1x_2^2 + b_{133}x_1x_3^2 + b_{223}x_2^2x_3$		
$+b_{233}x_2x_3^2 + b_{111}x_1^3 + b_{222}x_2^3 + b_{333}x_3^3$	Cubic interaction effects	

The equation above shows the interaction between the independent variables. This interaction can be calculated with statistical software, but it is impossible to measure in a linear system.

4 Experiments, Results, and Discussion

4.1 Lean Six Sigma Experimental Design

The design of experiment (DOE) is a test with series of runs, where changes are made to the controllable input variables of a process in order to understand the reason for the variation observed in the output response [58]. DOE can be used for methodical and detailed planning of an experiment before performing the activities. DOE is a technique that reduces the cost and time of a research while also improving the understanding of the process. The data from design of experiment can be transformed into mathematical model which computers can use for process simulation and optimization. Usually, DOE begins with the creation of process models as illustrated in Figure 30 [54]. The goal of design of experiment is to predict the result of responses when independent causes of variation are adjusted [59].

In this section, a systematic DOE will be outlined to understand the relationship between the output moisture percentage and the factors affecting the measurement accuracy of the microwave moisture measurement method. Since the effectiveness of design of experiment depend majorly on the factor selection, a fishbone or cause-and-effect diagram was designed together with the process owners to determine the most vital factors [54]. The fish bone diagram can be seen in Figure 29.

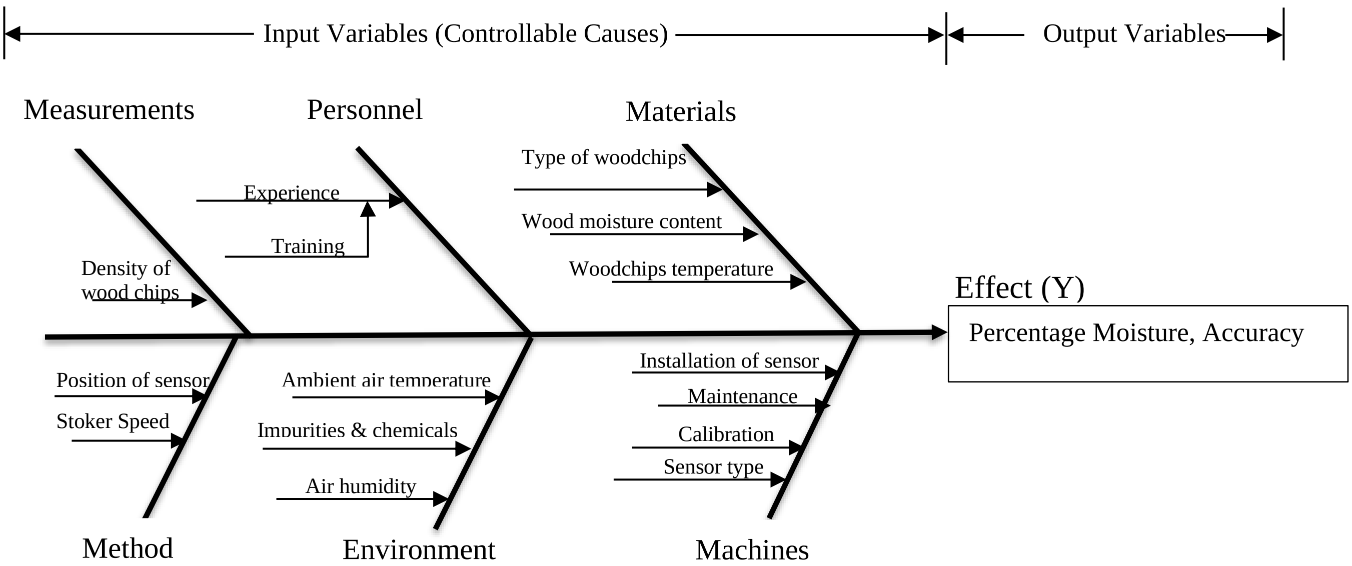

Figure 29.Fishbone diagram for root cause analysis of percentage moisture accuracy.

The most vital factors will then be used in the design of experiment. Another method would have been to determine the most vital factors by performing a DOE with all the multiple factors and after the vital factors have been determined, a new DOE is performed to understand the effects of these factors on the output moisture percentage. In any case the experiment should have a so many runs because the higher the number of runs, the better the accuracy of the experiment [54].

The process model is illustrated in Figure 30 using the most vital factors amongst the independent variables shown in Table 5.

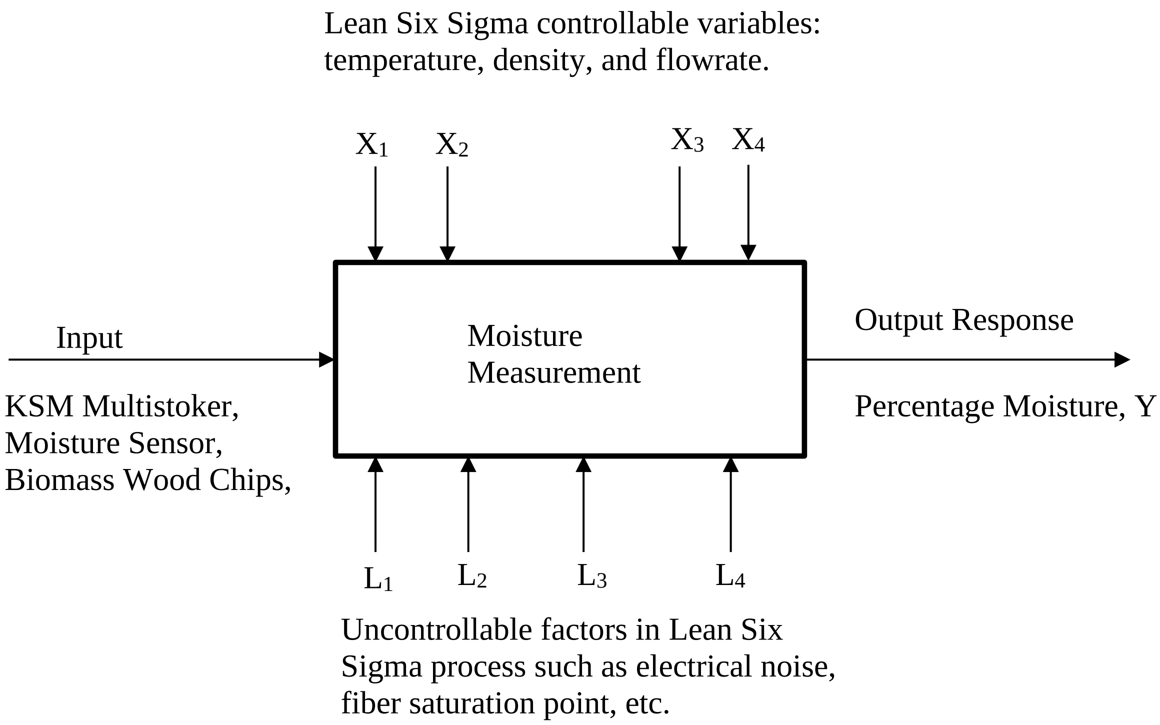

Figure 30. Model of a moisture measurement process with vital factors obtained from fishbone diagram.

Table 5. Cause Factors (Independent Controllable Variables).

	Controllable variables name	Low level (-1)	High level (+1)
1	A = Wood chips temperature (x_1)	0˚C	20˚C
2	B = Wood chips density (x_2)	300 kg/m^3	500 kg/m^3
3	C = Wood chips flowrate (x_3)	60 kg/hr	350 kg/hr

Table 6. Full Factorial Coded Design Matrix (Three Factors at Two Levels)

Run	A x_1	B x_2	C x_3	AB x_1x_2	AC x_1x_3	BC x_2x_3	ABC $x_1x_2x_3$
1	-1	-1	-1	+1	+1	+1	-1
2	-1	-1	+1	+1	-1	-1	+1
3	-1	+1	-1	-1	+1	-1	+1
4	-1	+1	+1	-1	-1	+1	-1
5	+1	-1	-1	-1	-1	+1	+1
6	+1	-1	+1	-1	+1	-1	-1
7	+1	+1	-1	+1	-1	-1	-1
8	+1	+1	+1	+1	+1	+1	+1

All the design of experiment runs can be carried out in order depending on the circumstances surrounding the test or it can be performed sequentially as shown in the table below.

Table 7. Actual values of experimental matrix with response before experimentation.

Run	x_1 (˚C)	x_2 (Kg/m^3)	x_3 (Kg/hr)	y_1	y_2	y_3	y ave.	Std Dev.
1	0	300	60					
2	0	300	350					
3	0	500	60					
4	0	500	350					
5	20	300	60					
6	20	300	350					
7	20	500	60					
8	20	500	350					

After the test is performed, it is important to perform an analysis of the data obtained from the experiment through the following stages [54]:

1. Create a table with the average, standard deviation, effects and half effects for the cause factors and interaction of responses.
2. Plot the response averages and standard deviation at the high and low values for each effect.
3. Create a Pareto chart of the absolute value of each effect for response and standard deviations.
4. Determine the critical variables that affect the response average and the standard deviation of the responses through careful observation of the Pareto chart.
5. Model the experiment with a response prediction equation.

In the designed process control system for measuring the moisture content in biomass wood chips, the input to the PID controller is a signal that gives the measure of the moisture content in the biomass wood chips [60]. This signal is produced by the microwave moisture sensor that measures the percentage of moisture content in the biomass wood chips. Usually, the signal produced from the microwave moisture sensor is an electrical output in analogue form. However, this analogue signal must be converted into a digital signal before it is used as an input to the PID controller. Analogue-to-digital convertors can be used to process the signal from analogue to digital form.

Microwave moisture sensors radiate an electromagnetic field on the biomass wood chips and due to the dipolar effect associated with water, the resonant frequency of the microwaves change as the moisture content in the biomass wood chips changes [35]. The variations in the resonant frequency are then scaled by calibration to produce a precise analogue output signal in the range of 0 – 20 mA or 4 – 20 mA. The process of calibration also provides the corresponding moisture content percentage.

An experiment was performed to understand the relationship that exists between the temperature of the biomass wood chips and the accuracy of the moisture measurement with the microwave moisture sensor. The microwave moisture sensor has an analogue output range between 0 – 20 mA. The first test performed was the measurement of a sample of biomass wood chips of 50 % moisture content with the microwave moisture sensor at room temperature. A signal value of 20 mA was obtained. The sample was then left overnight in the refrigerator and tested by the microwave moisture sensor. The relationship between the produced signal from the moisture sensor and the temperature change is shown in Figure 31. As the time increases, the biomass wood chips approach room temperature.

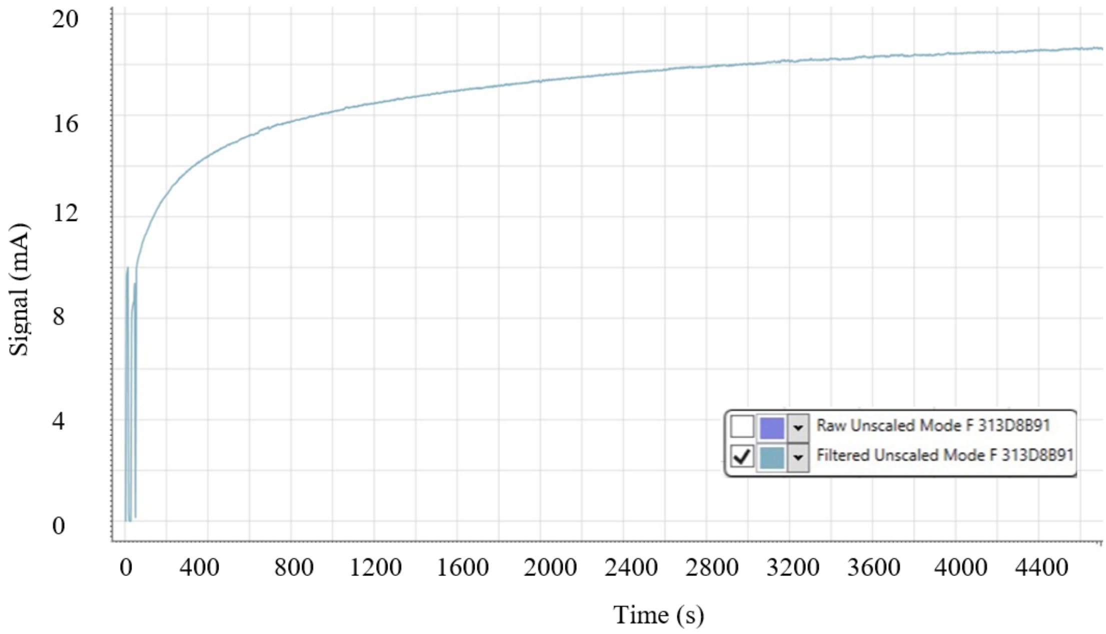

Figure 31. Relationship between microwave moisture sensor signal and the temperature of wood chips

The XY (scatter) chart in Figure 31 shows that the signal dropped to 10 mA and is unstable between 0 – 100 seconds while the biomass wood chips are totally frozen. However, above 400 seconds the signal begins to increase in relation to time. This proves that temperatures below 0 ˚C pose a challenge for the microwave moisture sensor.

4.2 Experimental Test

The wood chip samples should be obtained from the Dragefossen district heating facility in Fauske. The facility provides environmentally friendly heating to buildings in the municipality. The biomass furnace in the facility is fed with a mixture of biomass wood chips gotten from spruce, pine, and birch trees. The biomass samples should be collected in accordance with the sampling procedure defined by the international standard ISO 18135:2017 – Sampling of solid biofuels. The biomass wood chips should be delivered to the lab in airtight or hermitically sealed bags to maintain its original characteristics [36].

The test can be performed with both frozen and unfrozen biomass wood chips to observe the accuracy and repeatability of moisture content measurements when using the microwave moisture sensor under the conditions. Microwave moisture sensors work based on the use of electromagnetic radiation in the wavelength range of 1 mm to 30 cm on the sample woodchips [35].

To ensure accuracy and reproducibility when measuring the moisture content in the biomass woodchips, it is important to pay special attention to sample preparation. Based on the factors affecting moisture measurement with microwave moisture sensors, the samples can be divided into frozen and unfrozen woodchips and into different moisture content ranges. The usual moisture content range as observed by the process owners is between 20 % - 50 %. Therefore, the wood chips can be sorted into three moisture content classes as shown Table 8, with each of the three moisture content classes having three frozen samples and three unfrozen samples. To determine the initial moisture content ranges the NMR machine or other handheld moisture measuring devices can be used.

Table 8. Moisture content classes for experiment

Moisture Content Class (MCC)	**Moisture Content %**
MCC 1	20.0 – 29.9
MCC 2	30.0 – 39.9
MCC 3	40.0 – 49.9

After the sorting of the wood chips into the various moisture content classes, 6 subsamples can be taken from each class and put into airtight plastic bags. Three of the subsamples from each class should be stored in a freezer at very low temperatures for several days enough to freeze the wood chips. The other three subsamples from each class should be stored at about room temperature for several days. In total, 18 subsamples should be prepared with 9 frozen and 9 unfrozen.

The frozen subsamples should be taken out of the freezer to be measured, and the unfrozen subsamples can also be directly measured. For each subsample, several repeated measurements should be performed, and the measured moisture content should be recorded.

The reference method is the oven-drying method. The oven-drying method is a thermogravimetric method based on the separation of water from the biomass wood chips by heating the samples until vapor pressure equilibrium is reached between the sample and the drying oven. The reference moisture content of all the subsamples should be determined using the oven-drying method according to the ISO 18134-1:2022 standard (Solid biofuels – Determination of moisture content –Part 1: Reference method).

The reference moisture content for each subsample can be calculated as:

$$\text{Reference moisture} = \frac{(\text{weight of wet sample} - \text{weight of oven dry sample})}{\text{weight of wet sample}} \times 100 \qquad (21)$$

The accuracy of the microwave moisture sensor can then be determined by obtaining the difference between the two methods.

4.3 Lean Six Sigma Control Charts

Control charts can be used to monitor the moisture measurement percentages of the biomass wood chips in real time. Control charts can be used for control and maintenance of the moisture measurement process. Since the process owners (Dragefossen) expect the moisture content percentage of the biomass wood chips to be in the range of 20 – 50 %, it is important to define a control limit with the moisture content range that produces the optimum system efficiency and heat exchange performance. The moisture percentage obtained from the microwave moisture sensor should be plotted in a control chart, like in Figure 32.

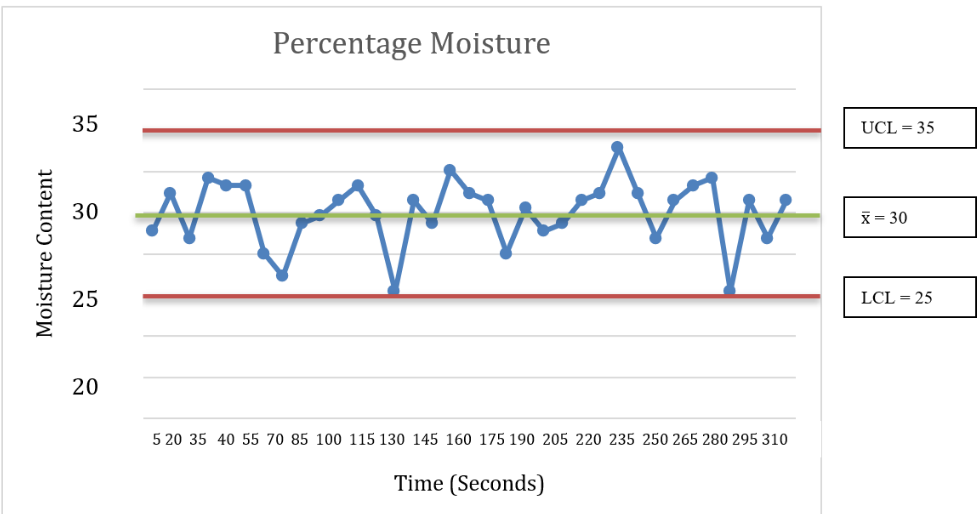

Figure 32. Process control chart for moisture content measurement.

Beyond the control limit, an output signal should be sent to the PID Controller to regulate the actuator. The actuator could be the stoker screw motor, the moving floor motor or the fans that provide air supply into the combustion chamber. The variable to be regulated depends on the process chemistry and understanding the process chemistry of the biomass heating system is vital for future research work in this field.

5 Conclusion

The designed process control system for regulating a combustion process using moisture content measurement in the biomass wood chips provides great opportunities for improving the overall efficiency of the district heating system. Based on the moisture content in the biomass wood chips, the process control system decides on which control variables should be adjusted to obtain optimal energy output per kg of biomass wood chips.

The systematic review of literature during this research revealed that even though a lot of studies have been performed to improve biomass combustion performance, there continues to be a lack of information about how moisture content in biomass wood chips affect the efficiency of biomass combustion systems. The research therefore utilizes tools like the SIPOC process map and the PID control loop to provide an understanding of the effects of moisture content in biomass wood chips on a biomass combustion system. This research also identified various types of moisture measuring methods that have been developed today and categorized them based on their mode of operation.

The research utilized a control system design process with seven major blocks in the design of the process control system for combustion regulation. The KSM Multistoker XXL was the specific biomass combustion system used for this research. The design process majorly involved the establishment of goals, control variables and specifications; the definition and modelling of the system; and the control system design, simulation, and analysis. The goals, control variables and specifications were established in partnership with Dragefossen (the process owners) with the aim of improving the efficiency of the KSM Multistoker XXL and filling a current research gap. Afterwards, the system was defined by establishing the system configuration and selecting the actuators and moisture sensor that would be used for process control. The microwave moisture sensor was selected amongst the other moisture measuring methods based on defined criteria and technical solutions for the installation of the microwave moisture sensor on the KSM Multistoker XXL were also discussed.

Lean Six Sigma tools were also integrated into the control system design process. The Lean Six Sigma process model diagram and the cause-and-effect diagram were used in system design and modelling to identify factors contributing to the accuracy of moisture measurement. The Lean Six Sigma design of experiment (DOE) was then used to design an experiment based on the critical factors identified. The reason for the design of experiment is to understand how the critical factors contribute to the variation in the accuracy of the moisture measurement. A preliminary test was performed to study the relationship between the temperature of the biomass wood chips and the accuracy of the signal produced from the microwave moisture sensor. The accuracy of the signal produced by the sensor affects the accuracy of the moisture measurement. An experimental test to be performed was also outlined to determine the accuracy of the microwave moisture sensor when compared with the oven drying method. Lean Six Sigma control charts were also recommended for process control and maintenance.

The performed experiments and recommended experiments in this research are effective contributions towards filling the current research gap regarding the influence of varying moisture content in biomass wood chips and the overall efficiency of biomass combustion systems. They also provide a basis for future research in this area.

Future studies may involve obtaining real data like the measured moisture content percentage of the biomass wood chips, biomass consumption rate (kg/hr) and other system performance data from the KSM Multistoker XXL after the installation of the microwave moisture sensor. This would enable the study into the effects of varying moisture content of biomass wood chips on the system performance of the KSM Multistoker XXL. Also, the combustion process in the combustion chamber can be studied through real-life experiments or simulations to fully understand how changes to the feed rate or air supply speed can affect the combustion process and effective heat exchange at the heat exchanger. These experiments and simulations can be performed with biomass wood chips of varying moisture content. Studies should also be performed to determine the moisture content range that makes for good combustion performance and heat exchange effectiveness. Finally, following the installation of the process control system, studies can be performed on the tuning of the PID controller for optimized system performance.

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Appendix

Appendix A – Task Description

Appendix B – Pre-study Report

Appendix C – Progress Report Part I

Appendix D – Progress Report Part II

UiT
THE ARCTIC
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OF NORWAY

Faculty of Engineering Science and Technology
Department of Industrial Engineering
Date: 15.11.2022

Industrial Engineering, Master Thesis 2022/2023, part I
INE-3900

Stud. Techn. Oluwatomi Abioye

Design of Process Control System for Measurement of Moisture Content in Biomass Feed

1. Introduction

The KSM Multistoker feeds wood chips as fuel for a combustion process that heats up water for a central heating system. The moisture content in biomass (wood chips) is typically reduced through natural drying. The rate of natural drying depends on the method of storage, storage period, temperature, and original moisture content of the biomass. Natural drying of biomass from a moisture content of about 50% to 30% takes almost six months and it requires another year to further reduce the moisture content to 15% [1]. Forced drying can also be done using heat dryers to further reduce the moisture content in the biomass. However, for large heaps of biomass stored for industrial use, there is always a varying amount of moisture content throughout the heap, and this is a cause of variation in the combustion performance and water heating efficiency. It is therefore important to design a process control system that can measure moisture content in the biomass feed and use this moisture content as a control parameter in the regulation of other parameters in the combustion process, such as the feed speed and the air feed thereby improving the efficiency of the combustion process.

Dragefossen is a power company established in 1928 to provide electricity for locals around the river Ytre-Tverrelva. Dragefossen currently has two power plants that both produce approximately 17 GWh per year and Dragefossen has gradually expanded its power line networks over the years through development and mergers. Dragefossen also has subsidiaries like Rognan Bioenergy and Fauske District Heating which engage in district heating and supply heat to large buildings in their locality, using virgin wood as the energy source [2].

The work tasks during phase I of the master thesis will mainly involve performing a literature study on the KSM Multistoker and the biomass combustion system to understand the mode of operation and have an adequate overview of the system processes. Also, the process regulation would be described with the aid of the SIPOC (Supplier, Input, Process, Output, Customer) process map and the PID (Proportional Integral Derivative) regulation, which is commonly used in the furnace industry for controlling process variables would also be used to describe the system processes.

The phase II of the master thesis will include mapping possible methods for measuring the water content in the biomass and suggesting technical solutions for the installation of these moisture measurement techniques or devices in the feeder to the KSM Multistoker. The aim of this project is to be able to measure the moisture content in the biomass feed and use this as a control parameter in the regulation of the combustion process.

2. Scope

1. Conduct a literature review on the biomass combustion system and the KSM Multistoker and describe the combustion reaction in the furnace with physical and chemical equations.
2. Describe the process regulation of the biomass combustion system using SIPOC process map and the Proportional Integral Derivative (PID) regulation with the goal of designing a PID regulation that uses the feed moisture content as an input factor so that the combustion process could be run with optimal energy output per kg biomass.
3. Map possible methods for measuring the water content in biomass.
4. Suggest technical solutions for the installation of moisture measurement techniques in the feeder to the KSM Multistoker with measured moisture content as an input to the PID regulation of the furnace.
5. Prepare a report detailing the result of findings and work performed.
6. Prepare a PowerPoint presentation on the performed work.

3. References

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4. General

Master thesis at Industrial Engineering is divided into two parts where the total allocated time is limited to 27 weeks fulltime work, corresponding to 45 study points.

Part I

In general, this part is an introduction to the project and is often a literature review especially adapted to meet the challenges within the project as well as to strengthen the competence of the candidates in a given field or direction. Part I study counts for 1/3 of the total time allocated to the project. This part has to be finished with a PowerPoint presentation and a written report after approximately 9 weeks fulltime work. Any written documentation of the thesis part I has to be enclosed or integrated in the final thesis reporting.

Part II

This is the main part of the master thesis within the Industrial Engineering education, and is a R&D project. The part II study counts for 2/3 of the total time allocated to the project. The final report with all accompanying documentation has to be handed in after approximately 18 weeks full-time work.

Within three weeks (full-time work) after the start of Part I, a pre-study report shall be prepared. The report has to include the following (a pre-study report template exists):

- An analysis of the work task's content specifically emphasizing the areas where new knowledge has to be gained.
- A description of the work packages that have to be performed. This description shall lead to a clear definition of the scope and extent of the total task to be performed.
- A time schedule for the project. The plan shall comprise a Gantt chart with specification of each individual activity/work package, their scheduled start and end dates, and a specification of project milestones.

The pre-study report is a part of the total thesis reporting and has to be enclosed with the final report. This includes also all progress reports made during the working period as well as the original task description. (A progress report template also exists.)

The final report should be edited as a research report with a summary, table of contents, conclusion, list of references, list of literature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also very important that exact references are given to any external sources used in the text.
All documentation developed during the work, e.g. computing programs, measuring results, drawings and models are parts of the final report and have to be enclosed.
The final report will be evaluated and basis for the grade of the master thesis.

If the work is performed in cooperation with an external organization, the candidate has to comply with the actual organization's company regulations and possible other relevant orders from the company's management. The candidate has no opportunity to interfere with the organization's information systems, manufacturing equipment or the like. If this should be relevant in connection with the execution of the tasks, it has to be authorized by the organization's management.

Any travel, copying, phone or other expenditures have to be covered by the students themselves, unless other agreements have been established.

If the candidate encounters unforeseen difficulties during the work, and if these difficulties warrant a reformulation of the tasks, these problems should be addressed immediately to the supervisor at the faculty.

5. Deadlines and participants

Date of hand out part I:	10th November 2022
Date of progress report:	6th December 2022 at 12:15. Progress report to be submitted to the Principal supervisor before the deadline.
Date of hand in part I	11th January 2023.
Presentation in part I:	PowerPoint presentation and give an oral presentation of the work on 13th January 2023.
Date of hand-out part II:	After presentation and approval of part I.
Date of hand in part II (final report):	15th May 2023.
Student(s):	Stud. techn. Oluwatomi Abioye, Address: Fiolstien 5A 8515 Narvik, Mobile Phone: +4746579212, E-mail: oab006@uit.no
Supervisor:	Professor Espen Johannessen, Faculty of Engineering Science and Technology, Office Phone: +4776966263, E-mail: espen.johannessen@uit.no
Co.-supervisor:	Jo Stian Hansen, Telecom Engineer, Dragefossen, Office Phone: +4795200334, E-mail: Jsh@dragefossen.no
Company liaison:	

Obligations and acceptance:	By signing this task document, I am/we are fully aware of the consequences of not following the respective delivery dates defined above. I also accept the obligations this task description implies.

I /we have received this task description:

Date: 08/11/2022

Students' signature:

....

Faculty of Engineering Science and Technology

Espen Johannessen

Professor

....

Faculty of Engineering Science and Technology
Department of Industrial Engineering

Attachment 2

Master of Science – Industrial Engineering

Master Thesis – Pre-Study Report

(INE-3900)

Design of a Process Control System for Combustion Regulation by Moisture Content Measurement in Biomass Feed

Author(s):
Oluwatomi Abioye

February 18, 2023

Title: *Design of Process Control System for Measurement of Moisture Content in Biomass Feed*	*Date:* 04.11.2022 *Classification:*
Author(s): Oluwatomi Abioye	*Number of Pages:* 9 *Number of Attachments:* 7
Subject Name: Master Thesis – Pre-Study Report	*Subject Code:* INE-3900
Faculty: Engineering Science and Technology	
Master Program: Industrial Engineering	
Supervisor: Espen Johannessen	
Co-supervisor: Jo Stian Hansen	
External Organization/Company: Dragefossen	
External Organization's/Company's Liaison:	
Keywords (max 10): Biomass, Bioenergy, SIPOC, PID, Process Control, Moisture Content, Combustion	

Abstract (max 150 words):

This project would describe the processes involved in heat generation using the KSM Multistoker, from the feeding process to the biomass combustion. SIPOC (suppliers, inputs, process, outputs, customers) process map which is a tool used in process mapping and improvement to highlight the inputs, outputs of a process and their interactions would be used to map the processes associated with the KSM Multistoker. Also, the Proportional Integral Derivative (PID) regulation, which is commonly used in the furnace industry for controlling process variables like temperature, speed and flow would also be used to describe the system processes in the KSM Multistoker. In addition, the possible methods for measuring water content in the biomass feed with suggested technical solutions for their installation will also be discussed.

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1. Introduction

Biomass has the capacity to generate a major part of the global renewable energy demands due to its large supply, versatility, and readily exploitable nature. Biomass can be produced from natural sources like wood waste, grasses, and fast-growing energy crops which are generally ubiquitous [1]. Bioenergy is generated from biomass that can be transformed to solid, liquid, and gaseous biofuels which is eventually used for production of heat, power, and fuel for transportation. Bioenergy currently supplies more energy than what wind, hydro, solar and geothermal renewable energy sources can provide altogether[2]. According to Eurostat, the statistical office of the European Union, 62% of energy used by households in the European Union in 2020 was for heating their homes[3]. The use of biomass as fuel for central heating systems would therefore be pivotal in solving global energy demands.

2. Background

The KSM Multistoker feeds wood chips as fuel for a combustion process that heats up water for a central heating system. The moisture content in biomass (wood chips) is typically reduced through natural drying. The rate of natural drying depends on the method of storage, storage period, temperature, and original moisture content of the biomass. Natural drying of biomass from a moisture content of about 50% to 30% takes almost six months and it requires another year to further reduce the moisture content to 15% [4]. Forced drying can also be done using heat dryers to further reduce the moisture content in the biomass. However, for large heaps of biomass stored for industrial use, there is always a varying amount of moisture content throughout the heap, and this is a cause of variation in the combustion performance and water heating efficiency. It is therefore important to design a process control system that can measure moisture content in the biomass feed and use this moisture content as a control parameter in the regulation of other parameters in the combustion process, such as the feed speed and the air feed thereby increasing the efficiency of the combustion process.

3. Problem statement

The KSM Multistoker feeds wood chips as fuel for a combustion process that heats up water for a central heating system. The wood chips have varying moisture content which causes variation of the combustion performance and water heating efficiency.

4. Project description/benefits

Design of a process control system that is able to measure the moisture content in the biomass feed. The moisture content is then used as a control parameter in the regulation of the combustion process, such as the feeding speed and the air feed.

5. Theory/hypothesis

Wood chips are used as fuel for the combustion process.
Wood chips are not totally dried and have varying moisture content.
Variation of moisture content in wood chips causes variation of the combustion performance and water heating efficiency.

6. Assumptions

Variation of moisture content in the wood chips is unavoidable.
Combustion performance would be increased if other combustion parameters like feeding speed and air feed are regulated with respect to the moisture content.

7. Risks

7.1 Risk Analysis Chart

Table 1: Probability analysis of the risks and their impact

Consequences (C)			Likelihood (Li)		
Category Definition	Consequences	Rating	Category Definition	Likelihood	Rating
High (H)	Severe	3	High (H)	Probable	3
Medium (M)	Medium Severity	2	Medium (M)	Possible	2
Low (L)	Insignificant	1	Low (L)	Remote	1

Consequences (C)	Rating(R)				Result	
	H	3	6	9		Unacceptable
	M	2	4	6		Tolerable
	L	1	2	3		Acceptable
		L	M	H		
	Likelihood (Li)					

Figure 1: Likelihood-Consequence Matrix

7.2 Risk Monitor

Table 2: Risk analysis

S/N	Risks	Possible or Feared Effect	Li	C	R	Mitigating Actions	Responsible Person
1	Failure to acquire relevant information pertinent to the project	Poorly researched work and inconclusive report.	2	3	6	Utilize platforms like Web of Science for access to a wide variety of world-class research	Oluwatomi
2	Poor interpretation of the project goals and objectives	Failure to include vital research and meet deadlines.	2	2	4	Discuss party expectations at early meetings	Oluwatomi
3	Lack of important feedback on project content, structure and progress	Incomplete project with unmet expectations	2	3	6	Continuous involvement of supervisors (UiT and Dragefossen)	Oluwatomi
4	Lack of time to conclude the project	Rushed and poorly delivered project	3	3	9	Proper planning and ensure the scope of project is suitable for the allotted time.	Oluwatomi
5	Insufficient involvement/assistance Dragefossen	Unmet expectations and delivery of irrelevant results	2	3	6	Discuss the situation with my supervisor. Raise the concern to Dragefossen.	Oluwatomi

7.3 Risk Mitigation

Table 3: Risk mitigation

S/N	Risks	Mitigating Actions	Li	C	R	Evaluation of Actions	Acceptable Not Accept
1	Failure to acquire relevant information pertinent to the project	Utilize platforms like Web of Science for access to a wide variety of world-class research	1	3	3	Easier access to relevant information.	Acceptable
2	Poor interpretation of the project goals and objectives	Discuss party expectations at early meetings	1	2	2	Clear understanding of project requirements.	Acceptable
3	Lack of important feedback on project content, structure and progress	Continuous involvement of supervisors (UiT and Dragefossen)	1	3	3	Adequate and timely feedback.	Acceptable
4	Lack of time to conclude the project	Proper planning and ensure the scope of project is suitable for the allotted time.	1	3	3	Timely completion of the project.	Acceptable
5	Insufficient involvement/assistance from Dragefossen	Discuss the situation with my supervisor. Raise the concern to Dragefossen.	1	3	3	Adequate industry perspective on the project and fulfilled expectations.	Acceptable

8. Objectives / Scope

- Conduct a literature review on the biomass combustion system and the KSM Multistoker and describe the combustion reaction in the furnace with physical and chemical equations.
- Describe the process regulation of the biomass combustion system using SIPOC process map and the Proportional Integral Derivative (PID) regulation with the goal of designing a PID regulation that uses the feed moisture content as an input factor so that the combustion process could be run with optimal energy output per kg biomass.
- Map possible methods for measuring the water content in biomass.
- Suggest technical solutions for the installation of moisture measurement techniques in the feeder to the KSM Multistoker with measured moisture content as an input to the PID regulation of the furnace.

9. Organization

9.1 Main activities

Table 4: Main activities

Main Activities	Sub Activities		Description	
	ID	Name	ID	Name
Planning	A	Project Management	A01	Scope Management
			A02	Risk Management
	B	Pre-Study Report	B01	Project definition
			B02	Planning the project
	C	Literature Review	C01	Biomass Combustion System
			C02	Design of process control systems
Research and Development	D	Research Study	D01	Moisture content measurement techniques
	E	Design	E01	Technical solutions for installation of moisture content measurement devices
			E02	Process control system
Completion	F	Final Report	F01	Report writing
			F02	Presentation of findings

9.2 Milestones

Table 5: Milestones

Phase	Milestone	ID	Event
Part I	08.11.2022	MS01	Delivery of Task Description I and Pre-Study Report
	06.12.2022	MS02	Delivery of Progress Report of Master Thesis Part I
	11.01.2023	MS03	Delivery of Master Thesis Part I
	13.01.2023	MS04	Presentation of Master Thesis Part I

Part II	14.01.2023	MS05	Start of Master Thesis Part II
	08.02.2023	MS06	Delivery of Master Thesis Task Description II and Pre-Study Report
	09.03.2023	MS07	Delivery and presentation of Progress Report of Master Thesis Part II
	14.04.2023	MS08	Delivery and presentation of Progress Report of Master Thesis Part II
	01.05.2023	MS09	Final presentation of the Master Thesis
	15.05.2021	MS10	Delivery of the Master Thesis

9.3 Progress monitoring

Progress monitoring helps the project to stay on track with the project budget. Progress monitoring in this project is performed with the aid of the Gantt Chart and other associated project management techniques

10. Costs

There are no anticipated costs during this project.

11. References

1. Demirbas, A., *Sustainable Biomass Production.* Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2006. **28**(10): p. 955-964.
2. Thrän, D., et al., *Bioenergy beyond the German "Energiewende"–Assessment framework for integrated bioenergy strategies.* Biomass and Bioenergy, 2020. **142**.
3. Eurostat. *Eurostat*. 2022; Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_products_used_in_the_residential_sector.
4. Haarlemmer, G., *Simulation study of improved biomass drying efficiency for biomass gasification plants by integration of the water gas shift section in the drying process.* Biomass and Bioenergy, 2015. **81**: p. 129-136.

12. Attachments

1. Activity description A
2. Activity description B
3. Activity description C
4. Activity description D

5. Activity description E
6. Activity description F
7. Gantt-chart

Attachment 4

Attachment 1: Activity description A

Project title: Design of Process Control System for Measurement of Moisture Content in Biomass Feed		*Date:* 04.11.2022	*Sign:* OA
Activity no: A	*Activity name:* Project Management		
Responsible: Oluwatomi Abioye			
Task description/intention: The progress of activities is monitored and evaluated as the project progresses			
Scope: Completed tasks are evaluated and upcoming tasks are planned.			
Method: Project management tools are used to manage progress of project			
Dependency: Continues through the lifecycle of the project.			
Documentation/results: Project management resources like Gantt chart and Risk Analysis chart.			
Written by: Oluwatomi Abioye		*Duration (days/weeks):* 27 weeks	

Attachment 2: Activity description B

Project title: Design of Process Control System for Measurement of Moisture Content in Biomass Feed		*Date:* 04.11.2022	*Sign:* OA
Activity no: B	*Activity name:* Pre-Study Report		
Responsible: Oluwatomi Abioye			
Task description/intention: Preliminary studies are carried out and planning of the project is done.			
Scope: Planning the project using project management tools and perform a brief study			
Method: Project management tools and Microsoft word			
Dependency: None			
Documentation/results: A written report			
Written by: Oluwatomi Abioye	*Duration (days/weeks):* 3 Weeks		

Attachment 3: Activity description C

<table>
<tr><td colspan="2">Project title:
Design of Process Control System for Measurement of Moisture Content in Biomass Feed</td><td>Date:
04.11.2022</td><td>Sign:
OA</td></tr>
<tr><td>Activity no:
C</td><td colspan="3">Activity name:
Literature Review</td></tr>
<tr><td colspan="4">Responsible:
Oluwatomi Abioye</td></tr>
<tr><td colspan="4">Task description/intention:
Carry out study on biomass combustion systems and designing of process control systems</td></tr>
<tr><td colspan="4">Scope:
Description of biomass combustion system and process regulation with SIPOC.</td></tr>
<tr><td colspan="4">Method:
Use of research tools, SIPOC process map</td></tr>
<tr><td colspan="4">Dependency:
Pre-study</td></tr>
<tr><td colspan="4">Documentation/results:
A written report</td></tr>
<tr><td colspan="2">Written by:
Oluwatomi Abioye</td><td colspan="2">Duration (days/weeks):
9 Weeks</td></tr>
</table>

Attachment 4: Activity description D

<table>
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Design of Process Control System for Measurement of Moisture Content in Biomass Feed</td><td>Date:
04.11.2022</td><td>Sign:
OA</td></tr>
<tr><td>Activity no:
D</td><td colspan="3">Activity name:
Research Study</td></tr>
<tr><td colspan="4">Responsible:
Oluwatomi Abioye</td></tr>
<tr><td colspan="4">Task description/intention:
Perform study on moisture content measurement techniques</td></tr>
<tr><td colspan="4">Scope:
Study various moisture content measurement methods and techniques</td></tr>
<tr><td colspan="4">Method:
Use of research tools</td></tr>
<tr><td colspan="4">Dependency:
Literature Review</td></tr>
<tr><td colspan="4">Documentation/results:
A written report</td></tr>
<tr><td colspan="2">Written by:
Oluwatomi Abioye</td><td colspan="2">Duration (days/weeks):
3 Weeks</td></tr>
</table>

Attachment 5: Activity description E

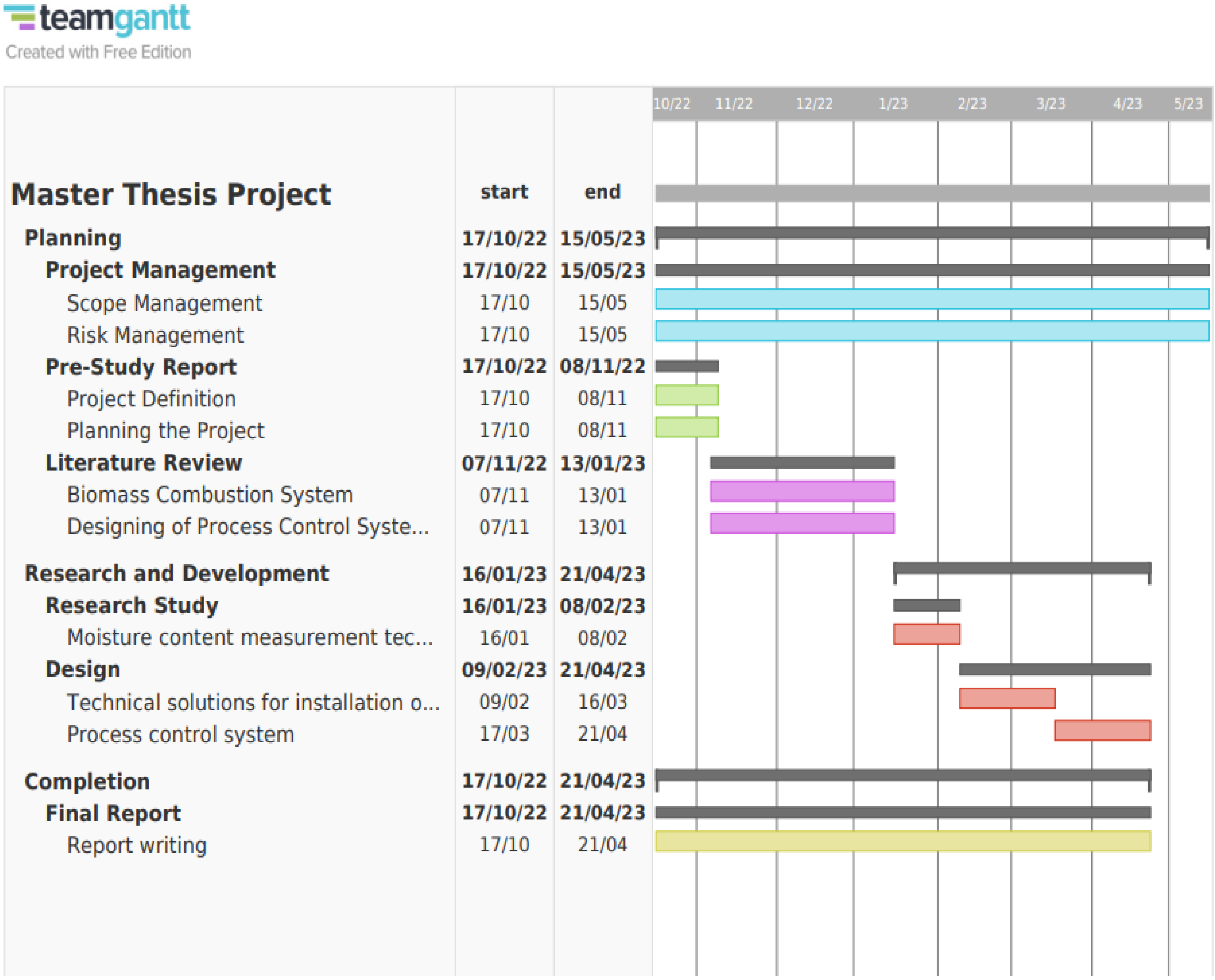
<table>
<tr><td colspan="2">Project title:
Design of Process Control System for Measurement of Moisture Content in Biomass Feed</td><td>Date:
04.11.2022</td><td>Sign:
OA</td></tr>
<tr><td>Activity no:
E</td><td colspan="3">Activity name:
Design</td></tr>
<tr><td colspan="4">Responsible:
Oluwatomi Abioye</td></tr>
<tr><td colspan="4">Task description/intention:
Design of process control system</td></tr>
<tr><td colspan="4">Scope:
Technical solutions for installation of moisture measurement in the feeder to the Multistoker.</td></tr>
<tr><td colspan="4">Method:
Use of study tools</td></tr>
<tr><td colspan="4">Dependency:
Research study</td></tr>
<tr><td colspan="4">Documentation/results:
A written report</td></tr>
<tr><td colspan="2">Written by:
Oluwatomi Abioye</td><td colspan="2">Duration (days/weeks):
10 Weeks</td></tr>
</table>

Attachment 6: Activity description F

Project title: Design of Process Control System for Measurement of Moisture Content in Biomass Feed	*Date:* 04.11.2022	*Sign:* OA

Activity no: F	*Activity name:* Final Report
Responsible: Oluwatomi Abioye	
Task description/intention: Documentation of the project report	
Scope: Written report that details project work	
Method: Use of research and writing tools	
Dependency: None	
Documentation/results: A final report would be documented	
Written by: Oluwatomi Abioye	*Duration (days/weeks):* 25

Attachment 7: Gantt Chart



Faculty of Engineering Science and Technology
Department of Industrial Engineering

Part I Progress Report

Progress Report:

Progress report no: 1	*Performed by:* Oluwatomi Abioye	*Date:* 06.12.2022
Project title: Design of Process Control System for Measurement of Moisture Content in Biomass Feed		
Main focus of work performed in this period: Literature review on biomass combustion system and the KSM Multistoker.		
Planned activities this period: To perform literature review on biomass combustion systems and the KSM Multistoker		
Real performed activities this period: So far I have completed the following tasks: Began literature review on biomass, biomass combustion systems and the KSM Multistoker. Gained basic understanding of PID controllers		
Reasons for possible delays: No delay experienced		
Describe how to catch up with possible delays: No delay experienced		
Requested changes compared with the original schedule: No changes required		
Main experiences this period: Basic understanding of biomass combustion systems, the KSM Multistoker and Proportional Integral Derivative (PID) controllers. Understanding how PID controllers can be integrated into simulations using COMSOL.		
Main focus next period: Complete literature review on biomass combustion systems and the KSM Multistoker. Describe the process regulation of the biomass combustion system using SIPOC process map and the PID regulation.		
Planned activities next period: To complete the literature review on biomass combustion systems and KSM Multistoker To fully describe the biomass combustion system using SIPOC process map and PID regulation		
Other:		

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Part II Progress Report

Progress Report:

Progress report no: II	*Performed by:* Oluwatomi Abioye	*Date:* 30.03.2023
Project title: Design of a Process Control System for Combustion Regulation by Moisture Content Measurement in Biomass Feed		
Main focus of work performed in this period: Literature review on biomass combustion systems and KSM Multistoker. Mapping of possible methods for measuring the water content in biomass.		
Planned activities this period: Completed literature review on biomass combustion systems and the KSM Multistoker Describe the process regulation of the biomass combustion system using SIPOC process map and the PID regulation. Mapping of possible methods for measuring the water content in biomass.		
Real performed activities this period: So far I have completed the following tasks: Literature review on biomass, biomass combustion systems and the KSM Multistoker. Mapping of possible methods for measuring the water content in biomass Selection of the most suitable moisture measurement technique		
Reasons for possible delays: No delay experienced		
Describe how to catch up with possible delays: No delay experienced		
Requested changes compared with the original schedule: No changes required		
Main experiences this period: Gained understanding of the biomass combustion systems Knowledge on the available moisture measurement sensors.		
Main focus next period: Suggest technical solutions for the installation of microwave moisture sensor in KSM multistoker Use Lean Six Sigma tools in process analysis, improvement, and control.		
Planned activities next period: Discuss the project using the control system design process. Use tools like control charts and fishbone diagrams in process analysis, improvement and control.		
Other:		