TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

INDUSTRIAL WOOD CHIP BOILERS CONTROL SYSTEM DESIGN AND IMPLEMENTATION

TÖÖSTUSLIKE PUIDUHAKKEKATELDE JUHTIMISSÜSTEEMI KAVANDAMINE JA RAKENDAMINE

MASTER THESIS

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THESIS TASK

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Thesis topic:
(in English) Industrial wood chip boilers control system design and implementation
(in Estonian) Tööstuslike puiduhakkekatelde juhtimussüsteemi kavandamine ja rakendamine.

Thesis main objectives:

1 Develop and implement a new control system
2 Tune and optimise all necessary PI controllers
3 Prepare requirement documentation

Thesis tasks and time schedule:

No	Task description	Deadline
1	Develop IO list	15.02.2024
2	Develop controls loops	30.04.2024
3	Prepare documentation	10.05.2024

Language: English **Deadline for submission of thesis:** "13." May. 2024a

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CONTENTS

List of abbreviations and terms

- ACN - Application and Control Node
- ACN MR - ACN Mounter in Rail
- CAD - Computer-aided design
- CPU - Central Processing Unit
- DCS - Distributed Control System
- I/O - Input/Output
- LHV - Lower Heating Value
- OLM - Optical Link Module
- PLC - Programmable Logic Controller

1.INTRODUCTION

Pärnu is a small town on the shores of the Baltic Sea. The city's population is 50934 [1] people, and it has been constantly growing in the last few years, the population has been constantly growing. The volume of residents and commercial space is also increasing [2]. These facts create an additional load on the existing district heating system. A local distributor, Gren AS heating and electricity, should adapt to the new requirements.

In addition to demographic reasons, the operational costs of the existing gas boiler systems have grown during the last few years because of regional instability and the trend of increasing gas prices. Natural gas prices have changed rapidly and often in the previous three years [3]. Such market behaviour complicates long-term relationships with partners and negatively influences the company's reputation.

Also, the European Union (EU) tightens the carbon footprint requirements [4]. Biomass is considered a fuel that helps conserve nature. The use of biomass allows the company to reduce its carbon footprint. Such fuel does not create an additional carbon footprint since it does not release ancient carbon bound in fossil fuels, only the carbon the lands have accumulated during their relatively short existence [5].

All these factors influenced the company and prompted them to negotiate with several companies to upgrade one of the oldest heating plants in Pärnu, Suur-Jõe boiler house. The boiler house has five boilers; two are biomass boilers, and the other are gas boilers. Each biomass boiler has a capacity of 7,5 megawatts. The boilers were installed in 1990 and operated until the end of 2010, after which they were decommissioned. Since the shutdown, the water part of the boiler has been filled with water and remained under pressure, regularly maintained.

In early 2023, a contract was signed for the overall renovation of the entire boiler house, and the boiler upgrade is a part of the project. As part of our project, Valmet has taken responsibility for updating the automation and control cabinets in accordance with modern standards and requirements. The main goal of the project is to create a reserve for the main station and to enhance the efficiency of the heating network. We are committed to ensuring that this project is implemented with high quality to meet the required standards.

As practical examples [6][7] demonstrated that bioenergy accounts for a significant share of renewable energy worldwide. It can meet a substantial portion of global energy demand in the next century. Proper management of biomass systems will contribute to meeting the requirements for carbon emission reduction.

1.1.Objectives

The master thesis will cover a few primary objectives:

1. Develop and implement a new control system for two biomass boilers to replace the outdated system.
2. Tune and optimise all necessary PI controllers.

To achieve these goals, it is necessary to update the existing control panels, establish a new industrial network, and develop and implement new control programs. All these tasks require knowledge of boiler control principles, industrial networks, electrical systems, process control principles, documentation development, and project management.

1.2.Scope

The primary focus is implementing operator displays, developing logical automation applications, updating hardware, and retuning PID control loops for a biomass-operated boiler system.The system was partitioned into multiple nodes to enhance the efficiency and manageability of the design process. This approach has proven to be successful and significantly simplified the design process, saving money and time [8].

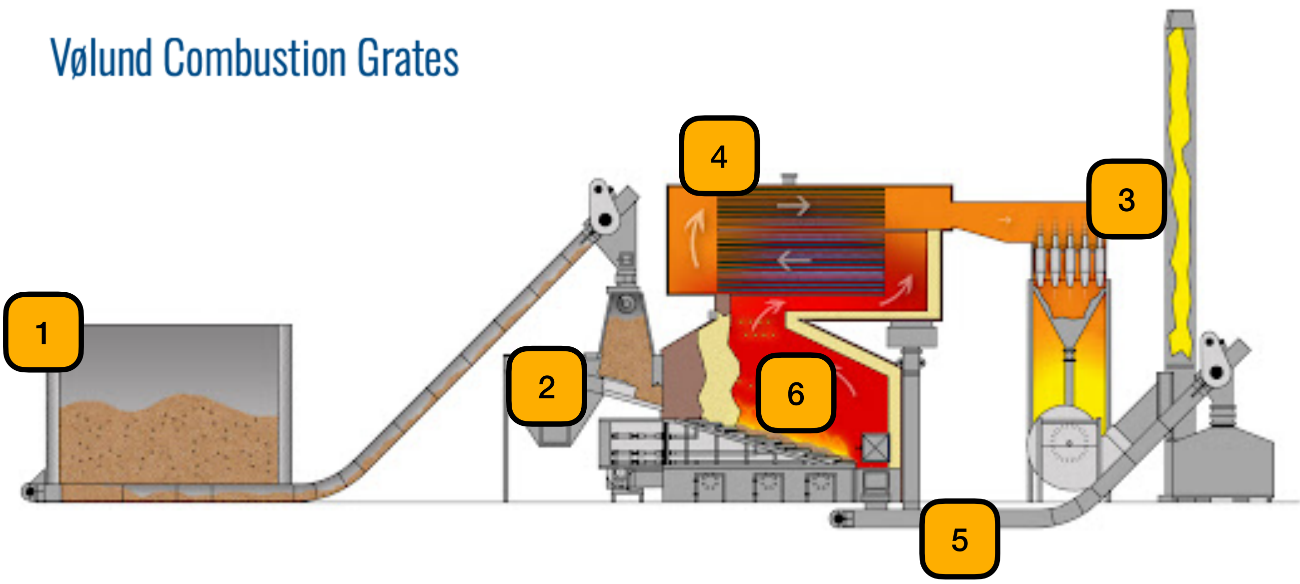


Figure 1.1: Schematic overview of grate combustion boiler system

The main nodes of the boiler system include all main subsystems show inn Figure 1.1 :

1. Fuel storage
2. Fuel processing and delivery.
3. Handling of exhaust gases
4. Water section

5. Ash removal
6. Combustion chamber

However, a single process controller manages all subsystems. Different components, such as heat exchanger valves, hydraulic stations, conveyors, pumps, and other equipment, must operate smoothly and be controlled precisely to ensure the system functions properly.

2. TECHNICAL BACKGROUND

This paragraph aims to introduce the reader to the theory of biomass boilers and their basic operating principles, describe the automation equipment, and provide an overview of the methods for optimising PID controllers.

To get heat from burning is one of the oldest ways to get heating energy. The first boilers appeared in ancient times and were primitive devices for heating water. However, they differed from the more complex and efficient designs we associate with the term "boiler".

Generating power through combustion is one of the oldest methods of obtaining heating energy. The initial boilers, primitive devices for heating water, date back to approximately 1500 years ago. Early examples in ancient Rome and China consisted of open containers where fire heated standing water. Over centuries, boiler technology evolved, leading to more efficient and safer designs than those primitive beginnings [9].

However, industrial steam boilers, as more complex and powerful devices, began to be widely used in industry in the 18th century, starting with the period of the Industrial Revolution. The first industrial boiler is considered to be the boiler designed by Thomas Servery. The installation consisted of a steam pump for pumping water out of mines. It required high-pressure steam to create a vacuum in the pumping chamber; for these purposes, the first boiler was made in the year 1698 [10].

2.1. Biomass as fuel

Biomass is a term that refers to a group of natural materials derived from plant or animal life waste [11]. These materials contain hydrocarbons, theoretically enabling their decomposition to yield energy under suitable conditions and processes. However, some materials can not be efficiently utilised for power or heat generation today by burning [12].

Solid biomass is an alternative to fossil fuels because it is a renewable energy source. Its growth and decomposition cycle is much shorter than that of fossil fuels, making biomass a cleaner energy source. During biomass combustion, only the carbon dioxide absorbed by the plant during its lifecycle is released, unlike fossil fuels, which add additional carbon to the atmosphere, accelerating climate change [13].

In Figure 2.1, the biomass lifecycle is shown, which ranges from 10 to 100 years, depending on the type of wood. In contrast, the lifecycle of fossil fuels is much longer. For example, coal formation can take 300 million to 360 million years, and less for younger types of coal.

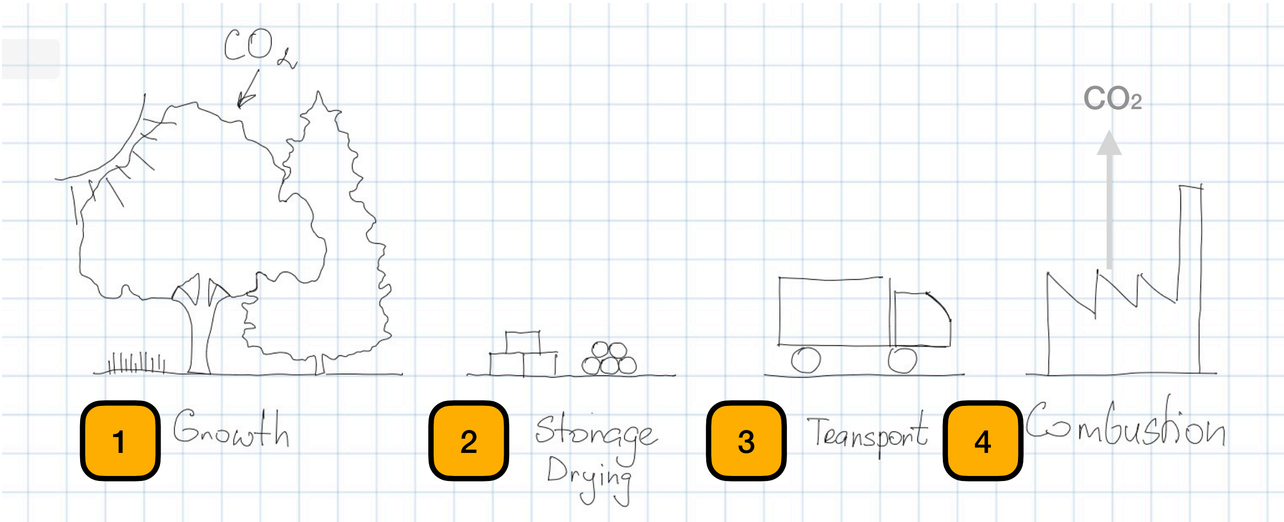


Figure 2.1: Life cycle stages of biomass from growth to combustion

1. During 10 to 100 years of growth, a tree absorbs carbon dioxide from the surrounding environment.
2. Biomass drying to reduce moisture content can take weeks to months.
3. The transportation process can take from an hour to several days.
4. Burning biomass for energy production happens relatively quickly, within a few minutes to several hours, depending on the size and power of the plant.

The study referenced as [14] provides a comprehensive comparison of various types of biogenic fuel based on key indicators such as humidity (w), ash content (a), lower calorific value (LHV), and basic chemical elements like carbon (C), hydrogen (H), nitrogen (N), sulfur(S), oxygen (O). The table indicates that there is an inverse relationship between moisture content and calorific value, with the calorific value increasing.

Table 2.1: Biomass fuel characteristics.

Sample	**w [%]**	**a [%]**	**LHV [MJ kg-1]**	**C [%]**	**H [%]**	**N [%]**	**S [%]**	**O [%]**
Wood pellets	7.2	0.27	16.951	47.27	6.62	0.05	0.06	45.73
Saw dust	7.43	0.39	16.212	46.29	6.48	0.7	0.06	46.08
Wood chips	10.54	0.62	15.894	45.18	6.12	0.18	0.03	47.87
Forestry residues	44.4	2.08	10.989	42.01	5.69	0.35	0.06	49.81
Corn cobs	6.87	2.25	15.181	45.02	6.37	0.64	0.11	45.61
Biochar	0.93	41.44	17.542	48.46	1.86	1.78	0.29	6.17

2.1.1.Forestry biomass

Estonia has over 2,3 million hectares of forest. As of 2018, the state owns 46% of the forest, and 48% is in private hands. According to statistics, Estonia has been increasing the total area of its forests over the last decade, with the area totalling 2235,6 thousand hectares in 2010 and reaching 2325 thousand hectares in 2022, marking a growth of 4% [15].

There are three types of biomass:

- **Primary**: Trunk of mature trees
- **Secondary:** Branches and crowns of mature trees and trunks of saplings removed during thinning.
- **Tertiary**: Residue from the processing of primary biomass obtained from forestry.

According to consumers, the majority of biomass in Estonia used for the production of heat and electricity is secondary and tertiary biomass. Wood chips are produced from hazard-prone trees, uprooted stumps, fallen saplings, cut shrubs, and storm damage mitigation. The chips are created by grinding wood into small pieces 1-5 cm in size. Wood chips typically have a high moisture content and can only be stored for a limited time.

2.1.2. Biomass combustion

Combustion is an exothermic reaction between fuel and oxygen, resulting in carbon dioxide and water vapour. The released heat can be used in many processes, though it is employed to heat water in boilers. Different furnace designs and combustion parameters can be selected to ensure optimal efficiency depending on the state and properties of the fuel being burned. Direct combustion is based on well-proven technologies. Biomass is considered the most important renewable fuel, as it allows for a predictable load, unlike other renewable energy sources such as solar and wind [16][17], and can be used as an alternative to coal.

Although coal, like other fossil fuels, coal has the exact origin as fuel and biomass, its structure and chemical properties are significantly different. Figure 2.2 shows typical types of wood fuel. As the diagram shows, wood chips are not subjected to any drying and have a high moisture content. The heating value of the fuel depends directly on the moisture content, and it is challenging to maintain stable combustion with a moisture content above 55% because different contents require different residence times in the furnace.

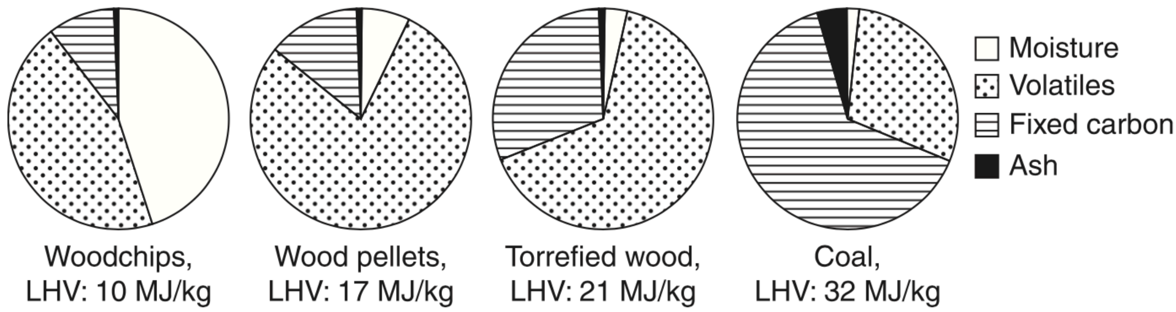


Figure 2.2: Comparative composition and energy content of biomass and coal

Biomass has a significantly higher volatile content than coal, and the ratio of carbon to volatiles is considerably less than one. The temperature at which volatile combustibles are released from biomass is lower than that of coal, which reduces the biomass's ignition temperature[18]. This fact requires special attention in the design or control of oxygen supply to the furnace to avoid delays in combustion. Volatile substances are released from the fuel as a gas upon heating and ignite when mixed with oxygen.

The combustion process of biomass, depicted in Figure 2.3, includes several key stages. In the initial phase of combustion (1), the biomass contains a significant amount of moisture. Before effective thermal energy can be released, a considerable amount of energy must be expended to heat and evaporate this water (2). This is illustrated in the stages where the biomass loses moisture, depicted as steam rising from the material.

The next stage of combustion begins with ignition (3), where the biomass actively burns with flame formation. At this stage, the release of thermal energy begins, continuing into the final stage (4). The last stage is characterised by a reduction in the volume of biomass and the formation of ash, indicating the completion of the energy release process (5).

These observations underscore the importance of the pre-heating and dehydration process of biomass as a critical step for the commencement of efficient combustion and energy release. Studying this process aids in optimising the combustion conditions of biomass to enhance its energy efficiency.

The commonly accepted combustion formula is:

$$C_xH_xO_xN_xS_x + n*(3.76N_2 + O_2) \rightarrow aCO_2 + bH_2O + cO_2 + dN_2 + eCO + fNO_x + gSO_x \qquad (2.1)$$

From this equation, fuel is converted into heat, carbon dioxide, and water [19]. However, this equation does not reflect the true nature of combustion. As per the combustion models, the

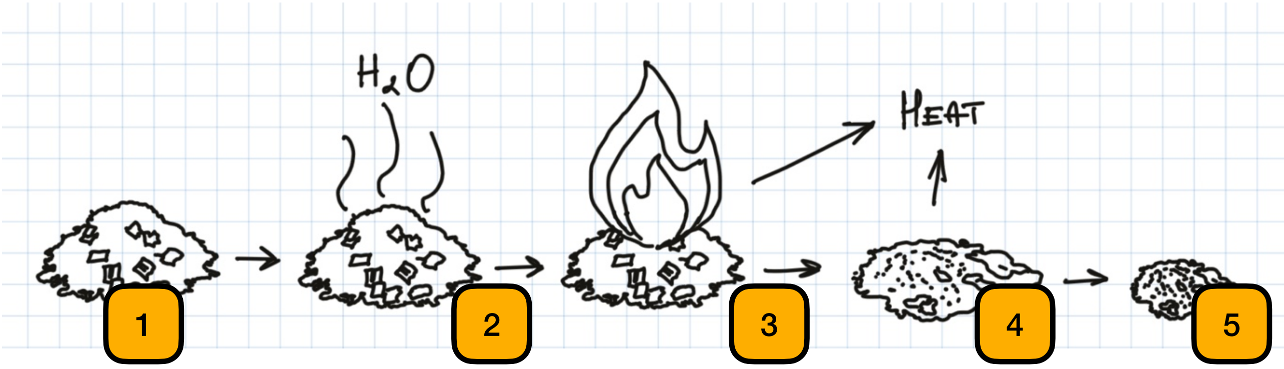


Figure 2.3: Biomass combustion process and energy release

process of methane combustion comprises an intricate sequence of 277 elementary stages, involving 49 distinct chemical species [20].

2.2. Existing method for biomass burning

The main techniques for biomass in heat and power applications are the same as for coal [21]. The most popular methods today are Grate-firing (GF), fluidised bed (FB), and pulverised fuel (PF). Each approach has its advantages and disadvantages. The choice of a specific technology depends on numerous factors, such as boiler capacity, fuel availability, regulatory approvals, and the region's future potential [22].

2.1.1 Grate - firing

Grate firing is a method used for heat and power production, which is equivalent to other biomass combustion techniques in terms of efficiency. However, it has an added advantage of being able to burn a wide range of fuels with varying moisture content, thereby reducing the fuel preparation requirement [23]. This makes grate firing an economical and efficient approach in biomass combustion. The biomass is pushed onto the grate by hydraulic pushers, and it slowly passes through the boiler while burning, while the air is supplied through the openings in the grate and above the flame, see Figure 2.4. This technique is particularly suitable for coarse-grained material and particles of different sizes, although the maximum power of the installation is restricted to 50 MW [22].

2.1.2 Fluidised bed

The fluidised bed is one of the most modern methods of biomass combustion. Power stations with fluidised bed boilers are more efficient and produce fewer emissions. The combustion process involves feeding biomass into the combustion chamber, where there is a pseudo-liquid layer, usually consisting of sand, through which air is supplied, giving the sand some liquid-like properties, a basic principle presented in Figure 2.5. Biomass mixes with this medium and is

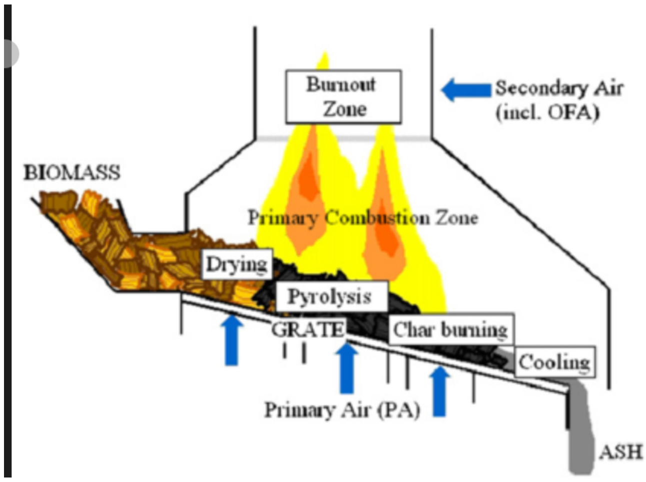


Figure 2.4: Grate combustion basic principle

suspended in a mixture. The temperature is adjusted to ensure smooth biomass gasification, making this method suitable for large and wetter materials compared to pulverised fuel.

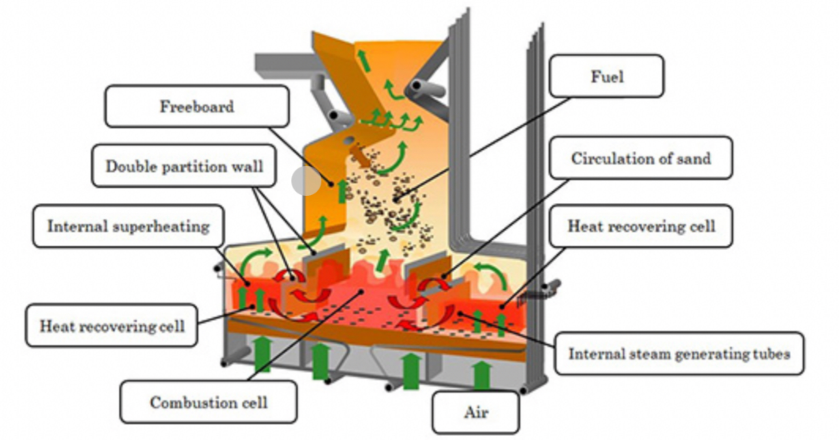


Figure 2.5: Schematic diagram of fluidized bed combustion process and components

Additionally, the process operates at a lower temperature, reducing nitrogen oxide and sulfur oxide emissions [23][24]. The power output of such power stations typically ranges from 30 to 300 MW. The relative complexity of installation and operation reduces its popularity. However, it is expected that in the future, all new large-scale biomass-to-energy conversion plants will operate with a fluidised bed, as it offers greater fuel flexibility compared to other methods.

2.1.3 Pulverised fuel

The pulverized fuel method is a commonly employed technique for upgrading coal or shale-fired boiler installations to meet modern EU standards and regulations. In this method, finely ground biomass is fed with air into the combustion chamber for burning, with the precondition that the biomass is adequately dry [25]. However, this has its own drawbacks. As coal or shale combustion requires higher temperatures, burning biomass can result in corrosion and slagging issues. Hence, the co-firing of biomass with coal is often adopted to mitigate problems arising from the high chloride content in biomass. Despite these challenges, boilers that use this method display high efficiency and can operate on a large scale of up to 600MW [26]. It is important to note that a significant portion of the energy produced is required for fuel drying and preparation.

2.3.Automation system

2.3.1.Distributed control system

A Distributed Control System (DCS) is a computerised process control system that is characterised by multiple autonomous controllers distributed throughout the system, which interact with each other. Each controller can share its local information with all neighbouring controllers to gain additional insight into the dynamics of the object. As a result, distributed controllers can coordinate their behaviour by transmitting and receiving information to and from other controllers within a certain neighbouring area. The benefits of this configuration include modularity, scalability, and reliability [27]. DCS is typically used in complex process applications such as paper production, power generation, and control. Unlike Programmable Logic Controller (PLC) solutions, DCS is generally sold with pre-designed control programs that only need to be customised to meet specific customer requirements.

The distributed system of controllers in a DCS provides an efficient and reliable method for process control. By sharing information, each controller can have a more comprehensive understanding of the dynamics of the system and adjust its behaviour accordingly. This results in a more coordinated and effective control system. The modularity provided by the distributed controllers enables the system to be easily scaled up or down as needed. Moreover, the reliability of the system is increased as multiple controllers can take over if one fails.

Automated inter-controller communication is essential in modern DCS and PLC, facilitating seamless data exchange and coordination across multiple control units. This technology underpins the efficiency of industrial automation, robotics, and complex manufacturing processes by allowing controllers to communicate autonomously, ensuring real-time operation and synchronisation. Critical features of this communication include the use of standardised protocols like Modbus and Profibus, the implementation of real-time data transfer, and the incorporation of robust security measures such as encryption to prevent unauthorised access. Additionally, mechanisms for fault tolerance, such as redundancy, are vital for maintaining operational continuity in the event of hardware failures. By enhancing the scalability and reliability of industrial systems, automated inter-controller communication plays a pivotal role in advancing the capabilities and resilience of modern industrial environments.

DCS is most commonly used in industries that require complex process control. For instance, in paper production, the DCS can be used to monitor and control the entire process from pulp preparation to finished paper rolls. In power generation, the DCS can be used to monitor and control the different parts of a power plant, such as turbines, generators, and boilers. Finally, in control applications, the DCS can be used to monitor and control a wide variety of systems, including environmental control systems.

Both DCS and PLC comply with the international IEC standard. The IEC 61131-3 [28] standard plays a key role in the programming of Programmable Logic Controllers (PLC). It offers five programming languages, each suited to different styles and requirements of design in industrial automation. These languages include Ladder Diagram (LD), which is ideal for traditional control tasks based on relay logic; Function Block Diagram (FBD), used for structuring the control system with functional blocks; Structured Text (ST), a textual programming language similar to Pascal, designed for more complex algorithms; Instruction List (IL), similar to assembly language, for detailed low-level control; and Sequential Function Chart (SFC), intended for describing sequential processes.

The IEC 61499 standard expands the capabilities of IEC 61131-3 by introducing concepts for creating distributed control systems that enhance the modularity and scalability of systems. This standard simplifies the integration of multifunctional devices across various platforms and manufacturers, supporting more complex and flexible system architectures. It also emphasises the importance of interoperability and component reuse, which are crucial for modern industrial applications where rapid adaptation and scaling of production processes are required.

2.3.2. Valmet DCS hardware

The main difference between a DCS system and a PLC is the absence of a single critical point whose temporary shutdown would lead to the failure of the entire process. This can be observed in the equipment necessary for implementing a DCS system, Figure 2.6 [29].

1. **Operator Station:** This station allows monitoring, managing, and analysis of the system. It offers an operator or engineer a wide range of capabilities to influence the system. It has features for creating graphs and displaying signals from a single subsystem or the entire system.
2. **Controller:** An industrial computer that performs all the computational operations for system control.
3. **Operator Interface:** Allows managers to monitor and analyse the system in real-time.

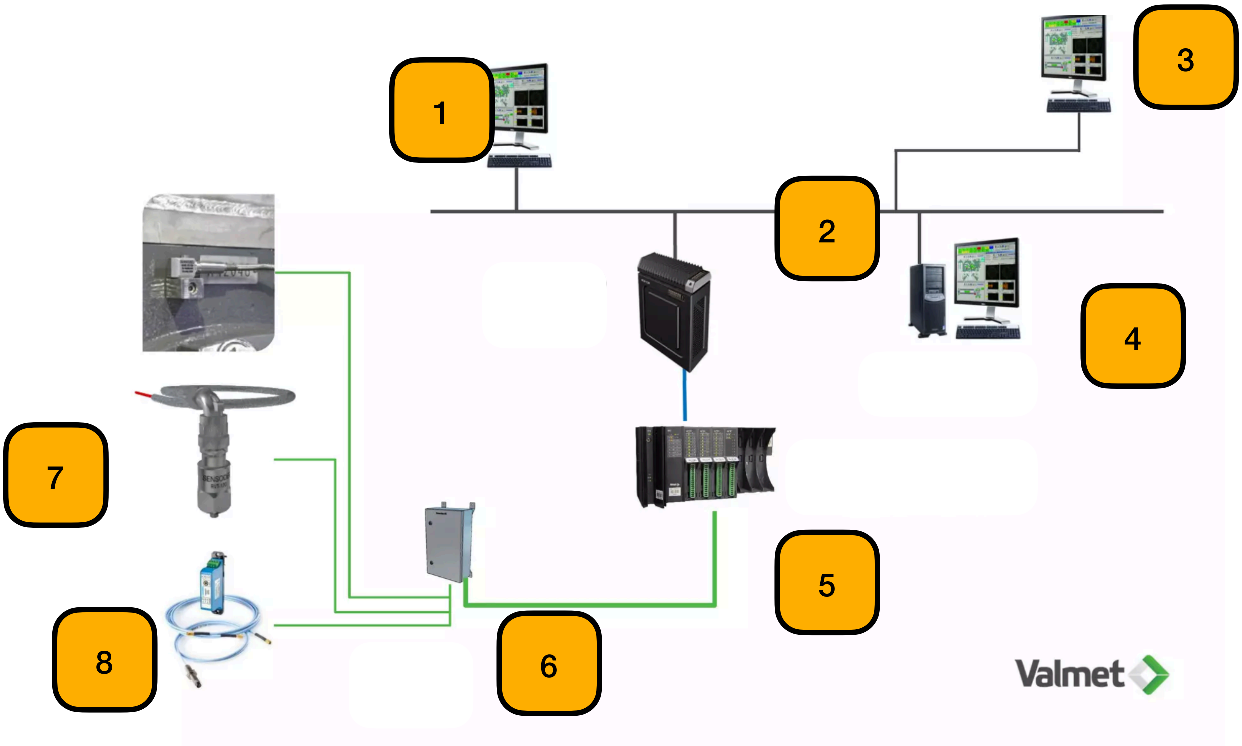


Figure 2.6: Basic system layout

4. **Computer or Server**: Designed to collect data from all necessary system points. For example, to save pressure readings over the last few years.
5. **Input/Output Cards:** These cards allow reading the state of equipment and input signals from devices into the Valmet DNA system.
6. **Field Cabinet:** An intermediate cabinet for connecting equipment and trunk cables.
7. **Sensors:** Read the state of the process.
8. **Actuators**: device that are used to perform motion

Valmet offers a variety of controllers for different needs and I/O capacities. Powerful industrial computers designed to be installed in standard server racks can handle a large number of input signals and run programs with various execution cycles. However, more compact and less expensive solutions are also available. Table 1 presents a comprehensive analysis of various controllers to provide a detailed and insightful comparison.

Table 2.3.1 Valmet controllers basic parameters

NAME	Mounting	Supply voltage	Operating system	Min. Control cycle	Redundancy support	Autostart	Extension slots for PCLe cards	Max. Fieldbus amount	Conformal coating	Cooling	Marine type approved
ACN MR	Rail	+24 VDC	Linux	5 ms	Yes	Yes	0	5	Yes (option)	Passive	Yes
ACN CS	Panel/ shelf	+24 VDC	Linux	20 ms	Yes	Yes	2	5	Yes (option)	Passive	Yes
ACN RT	19” rack/ shelf	+24 VDC / 110-230 VAC	Linux	20 ms	Yes	Yes	5	7	Yes (option)	Active	Yes

However, all these machines share that they are single-board industrial computers of increased reliability for operation in an industrial environment. Such machines can operate 24 hours a day, seven days a week, for many years without reboots or maintenance. These devices monitor and control processes in various industrial fields, maintaining efficiency and reliability.

The ACN controllers are part of the Valmet DNA process control system, which integrates control, safety, and monitoring processes into a single system. The ACN MR G2, like other products in this line, is designed to ensure reliability, responsiveness, and scalability in managing production processes. These controllers support a wide range of industrial communications and can be integrated with various systems and equipment.

To connect the field devices with the controllers, I/O modules are used along with the necessary equipment, such as mounting boards, power supplies, and routers. I/O modules are designed to collect and transmit data from field devices to the control system and back, establishing communication between the physical processes and the control software. The cards can be divided into two broad categories: digital and analogue. Digital cards are designed to identify two states, one "true" and zero "false". Analogue cards allow for the connection and operating with current or voltage signals.

2.4.Automation engineering environment

An automation system is a complex engineering solution with various devices, algorithms, and software designed to make decisions for clearly defined tasks. Many approaches and methods exist for formulating management and control tasks. Below, three approaches will be described, with their advantages and disadvantages.

1. The most popular and widespread approach is the classical approach. This approach is based on classical control methods, such as analytical control methods, feedback theory, and simple regulators like ON/OFF and PID.
The classical approach is simple to implement, and the mathematical methods are predictable and well-studied. However, it has several disadvantages, such as inefficiency in complex or nonlinear systems.

2. Model-oriented approach. This includes methods such as linear and nonlinear programming, optimisation methods, and control theory of systems with distributed parameters. This approach allows for a thorough study of system behaviour, but high accuracy comes at the cost of complex calculations and a labour-intensive development process.

3. Use of neural networks. This approach is based on the application of artificial intelligence methods, such as genetic algorithms, neural networks, and machine learning. This approach can overcome the minuses of the model-oriented approach, is capable of adapting to various conditions and nonlinear dependencies, and allows for considering a large volume of data and experience for decision-making. On the other hand, it requires a massive amount of data for training, it is difficult to interpret and explain the decisions made, and it has issues with reliability and security.

A modern automation system usually uses a combination of these methods to solve specific subtasks. For example, the engine's rotation speed is regulated using a classical PID controller, but the operator's advice for selecting the correct mode for burning the optimal amount of fuel can be based on a neural network, which utilises parameters such as wind speed, temperature, and other indicators.

2.4.1. Automation language

Automation language is a unique programming language designed for automating processes and controlling systems based on functional blocks and universal data types. It is used to create operations in Valmet DNA, allow logical operations and comparison operations, and present graphics in the form of a list [30]. Fully compatible with IEC 61131 FBD part, discussed previously.

Automation language allows engineers to create a clear and logical model of the process in Valmet DNA and configure all necessary data and variables. Thanks to its specialisation, the language provides a broad level of user support. It offers higher efficiency in automation design than general-purpose languages. Notable software packages provide an efficient user interface for the application designer, including all the tools for application design, such as ready-to-use functional blocks.

Communication between functional blocks and programs is based on name-based communication technology, which utilises unique identifiers rather than traditional IP addresses to manage and route data. This approach significantly enhances the efficiency of data retrieval and distribution across diverse computing environments by allowing systems to request and retrieve data based on names irrespective of their physical locations. This decouples the relationship between data producers and consumers, facilitates robust caching mechanisms at various network nodes, and ensures content is delivered more swiftly and reliably, making it especially suitable for dynamic and decentralised networks like those in IoT and cloud computing applications.

An application made in Automation language consists of several logical modules. Modules are the smallest software blocks that can be individually loaded onto the server. For example, there could be modules such as a measurement loop, sequence control program, motor control program, or a display on the monitor screen. The modules are made up of standard types, the same types that are contained in the server's libraries. The modules interact with each other by copying the necessary data and forming the automation system together. Despite the use of strictly typed blocks, Automation language does not provide the capability to get a graphical representation of the loaded application.

This approach is possible due to the strict definition of data formats incorporating a specific information set. In Automation language, several data formats are distinguished: primitive types, structured types, arrays, and fixed frame tables.

Primitive types: Basic data types in the Valmet Automation language are also used to get derived primitive types.

- Unsigned integers, size 2 bytes, range (0 … 65535)
- Single precision floating point, size 4 bytes, range (±$(10^{-38} \ldots 10^{38}$)
- Derived primitive types are formed by renaming basic types.

Structured types are data based on other types and can contain both themselves and primitive types grouped within.
Data type: "ana" consists of unsigned integers (fails) and single-precision floating points (values), for example (2, 9.54). In fails 7bit are used to represent various fail states and other reserved for future use.

Arrays: As in other programming languages, an array is a data structure whose elements belong to the same primitive or structured type. Any element of the array can be referenced by its index. Valmet Automation language allows the use of three-dimensional arrays.

Fixed-frame tables are structures with a fixed frame and a predefined type. They contain a table whose structure can be modified during configuration and execution. This allows for a predefined structure to be dynamically adjusted as needed, providing flexibility within the constraints of a fixed-frame format.

However, any program primarily consists of functional blocks. Functional blocks are a predefined type of data that performs a clearly defined task. Each functional block can operate with many of the aforementioned types of data. Each block has input, output, and configuration parameters. Only identical types of data can be connected to each other. Also, each block has numerous internal parameters that cannot be changed during operation. Below is a brief overview of the main standard blocks used in the daily work of an application engineer:

2.4.2.PID block

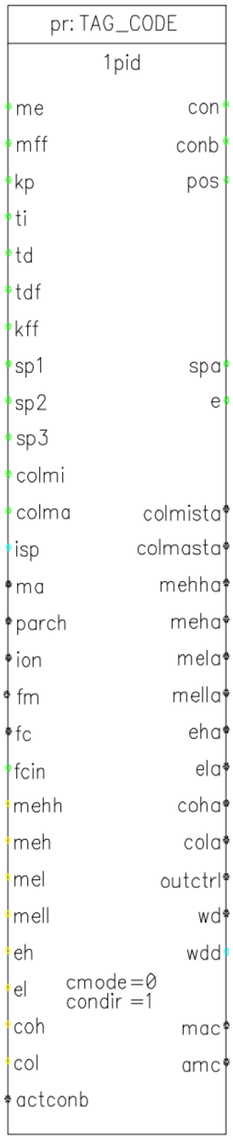
In Valmet, the PID controller is presented as a software product in the form of a functional block, Figure 2.7, based on a CAD engineering system. The functional block of the PID controller generates its control signal (con) based on the active set value (spa) and the measured value (me). The function of the PID is to maintain the measured value equal to the set value regardless of any disturbances.

The controller algorithm includes parts traditionally presented in any PID regulator, and their impact on the output signal can be activated or deactivated. Some possible components are proportional, Integral, and Derivative components, a low-pass filter for the D-part, output signal offset, output signal limitation, bump-less transfer switch, and absolute and incremental control.

Unlike the classical implementation in Valmet DNA, the D-part is generated from the measured value, not the error value. Changing, for example, the set value will not cause a jump in the control output, as in a conventional controller.

The PID controller mainly has two modes of operation: MANUAL and AUTOMATIC, which are selected based on the input signals ma, mac, and amc. In manual control mode, the value of the output signal con is manually set from the control room; in automatic mode, it is calculated based on the measured value (me), the active set value (spa), the feedforward channel (mff), and the offset (bias).

The necessary control elements are introduced for use with configuration parameters pu (P-element), squ (squaring), iu (I-element), deu (D-element), and ffu (feedforward channel). The offset is always considered (it applies only to P-action). Still, it affects control only when the offset parameter differs from zero (provides an output value for a zero error value).



me	Measured value
kp	P term gain
ti	Integral action time constant [s]
td	Derivative action time constant [s]
sp	Local setpoint
con	Control, output signal
spa	Active setpoint value
e	Error (e = spa - me)
sp2	Remote setpoinnt
sp3	Computer setpoint
colmi	Minimum limit of control output
colma	Maximum limit of control output
isp	Setpoint selection index
ma	Manual/automatic mode
fin	Forced control input
wd	Watchdog
wdd	Watchdog data (Bit encoded faults)

Figure 2.7: PID block representation

The tuning parameters of the algorithm kp, ti, td, tdf, and kff are scaled in the regulator so that they correspond to the execution interval of the functional block; thus, for example, the times of integral and differential action can be set in seconds regardless of the execution interval. The scaling is initiated by setting the parch input. When parameters are manually changed from the control room, the parch input will be set automatically; however, if any parameters are connected from the process control server, the parch must be set to the time of one execution cycle for scaling the parameters due to changes. The placement of new values also depends on the part parameter, which indicates whether the regulator's integrator should absorb a jump in the output caused by a parameter change.

The precise tuning of the parameters of a PID controller is a critical aspect in achieving an optimal control response. Failure to set the PID controller parameters accurately may lead to poor control performance, overshoots, and oscillations. Therefore, a thorough understanding of the PID control scheme and the effects of each parameter on the control response is necessary. It is essential to adopt a systematic approach in tuning the PID controller parameters to ensure that the controller achieves satisfactory performance. Valmet’s implementation may support several tuning techniques:

- **Ziegler - Nichols Method**: A well-known method for setting initial PID parameters that involves bringing the system to the verge of instability and then backing off to achieve a desirable response
- **Cohen-Coon Method:** A more refined approach that aims to improve the controller's response time and stability, suitable for processes where the dynamics are reasonably well understood.
- **Trial and Error**: In many real-world applications, especially where process dynamics are complex or poorly modelled, manual tuning through trial and error remains a common practice. Operators adjust settings based on observed performance and process requirements
- **Autotune software:** A sophisticated technology that leverages algorithms to automatically adjust PID parameters, ensuring optimal performance without manual intervention. This method is particularly beneficial in environments where conditions change rapidly, allowing for continuous process optimisation.

2.4.3.Valve block

In Valmet DNA, there are two types of control blocks for valves. One of them is designed to control ON/OFF valves, the other offers the capability to control valves with position determination.

Figure 2.8 shows a control system for motor-operated valves used in the Distributed Control System (DCS). The diagram describes the logic of state indication, control, and monitoring of various types of valves (A, B, C, D).

- Valve type A: Standard motor-operated valve. Capable of automatic control, open/close, and interlocking.
- Valve type B: Similar to type A, but with additional position control.
- Valve type C: Compact motor-operated valve with detailed position control.

At the top of the diagram, there are symbols for the DCS display, such as colour indications and flashing symbols for various states for example, open/closed, operational, locked, fault, and manual/automatic control.

The diagram also includes descriptions of monitoring algorithms and error signalling, including switching from automatic to manual mode in case of faults, as well as the process of manually restarting the open/close control functions.

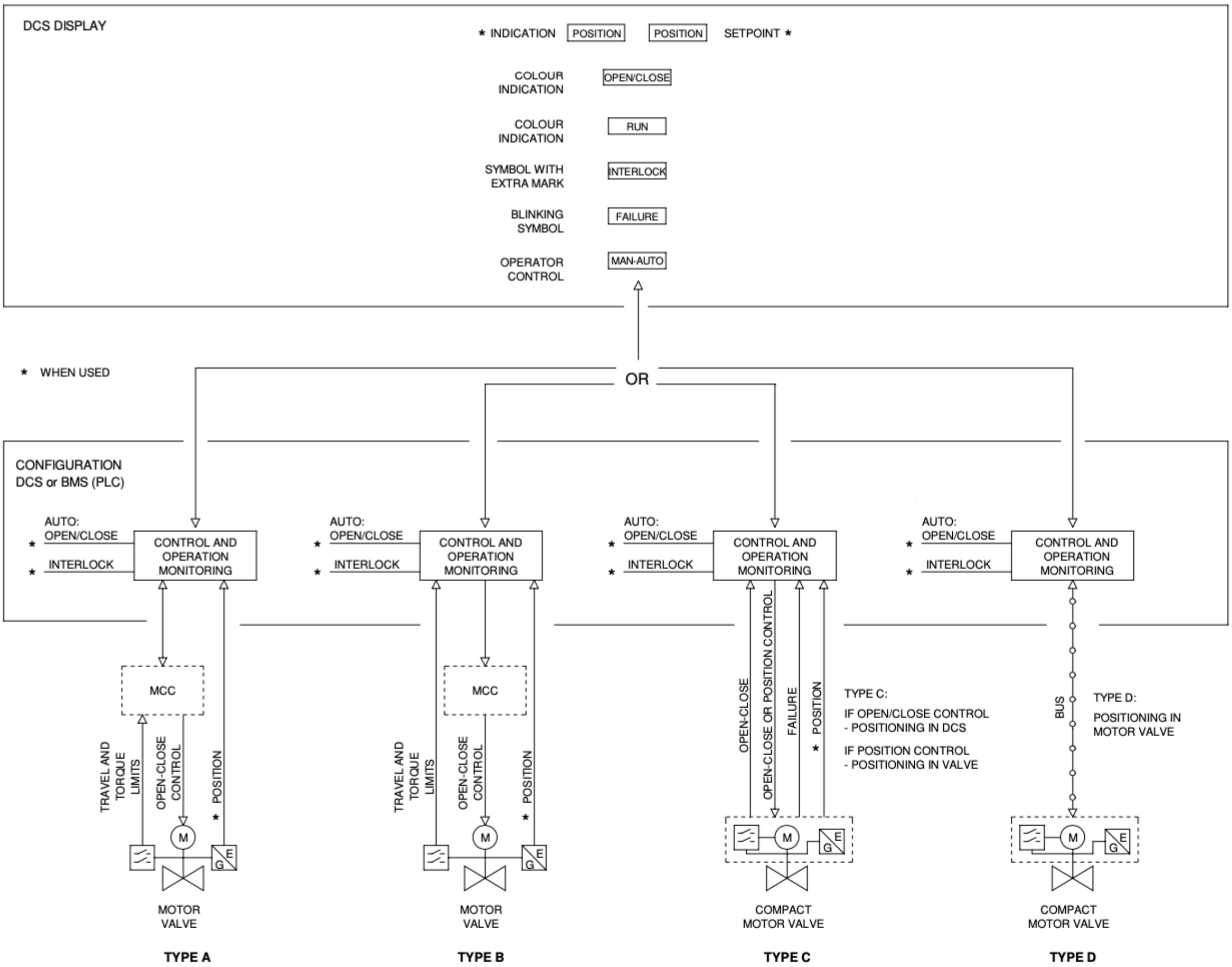


Figure 2.8: Schematic of DCS control and monitoring for motor-operated valves

2.4.4. Motor block

The motor control block is designed to control an electric motor directly or use a frequency converter. Inside the block, there are numerous standard parameters that can be used to control the electric motor. Figure 2.9 shows the control schematic and an operator display, allowing monitoring of the equipment's condition. The image indicates that the block has a range of alarms and signals available to the operator at the operator station in the DCS system.

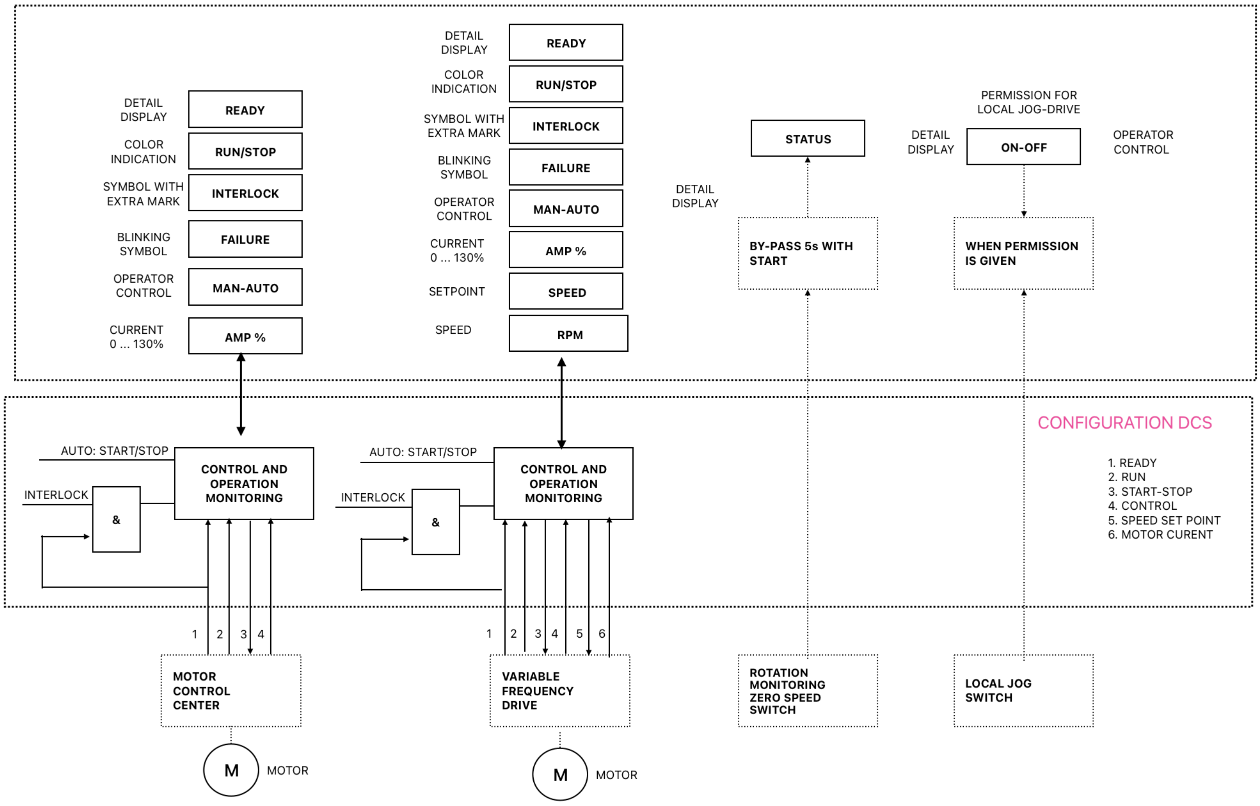
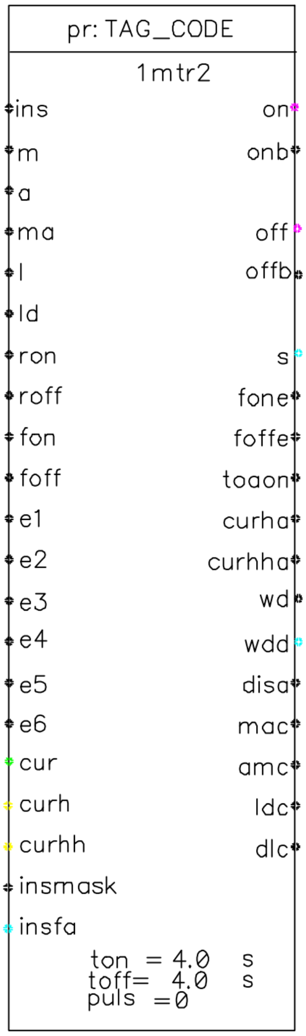


Figure 2.9: Schematic overview of DCS motor operations

The block has the capability to control the motor in pulse mode, and it also reads the control signal to determine whether the motor has been successfully started or not within a specified period of time. The main parameters are as follows, Figure 2.10.



ins	Motor status, brought in directly from the field
m	Manual control mode
a	Automatic control mode
l	Local control mode
ma	Manual / Auto selection
mac	Permits switching from manual to automatic mode
amc	Permits switching from automatic to manual mode
ld	Local / PCS selection
ldc	Local-to-PCS change allowed
dlc	PCS-to local change allowed
ron	Permits the starting of a stopped motor; does not affect a running motor

Figure 2.10: mtr2 block representation and basic inputs

3. OLD CONTROL SYSTEM

The goal of this paragraph is to describe the solution that existed before the update began. Its purpose is to analyse and understand the technical decisions that were made. This involves looking at the original state of the system and process, the reasoning behind the existing setup, and the specific technological or methodological solutions that were implemented. Understanding these aspects is crucial for identifying the strengths and limitations of the previous solution, which in turn determines the direction and scale of subsequent updates.

By critically evaluating the last state, we can ensure that updates will not only address any shortcomings but also develop and improve the successful elements of the original control system. This will maintain the necessary minimum staff and the time required to ensure the station's operation. Including enabling its remote management from the main station building.

3.1.Boiler system overview

The station was designed for burning wood chips, peat, and their mixture. Each of the boilers is capable of producing 7,5 MW of thermal energy when burning wood chips with a moisture content of 55%. The estimated fuel consumption at 100% load is 4200 kg/h, with the calorific value of the wood chips being 9,26 MJ/kg. The boiler manufacturer guarantees the following exhaust gas composition when all technological prescriptions are adhered to:

Table 3.1 Guarantee values for wood chips.

Parameter	Units	Maximum value	Minimum value
Boiler load	MW	15 (2 x 7.5)	2,25 (one boiler)
Excess air		1,55	1,74
0_2 content	%	7,5	8,9
CO	Ppm	300	500
Flue gas temperature after boiler	°C	120	120
Boiler efficiency	%	88,5	84,7

The client partially provided the boiler room drawings. However, some of them were altered or lost. The boilers were last operated in 2009, and since then, the automation equipment and measuring devices have been turned off and used as donor parts for the main station and other client facilities.

3.1.1. Fuel store

In Pärnu, one of the common types of biomass storage used is an underground concrete pool, as it offers several advantages, such as the capability for trucks to self-unload using gravity without the need for additional mechanical equipment. On the front side is an access route for trucks, and on the opposite side is the first conveyor.

Fuel is transported from the storage to the ice separator, located above the first conveyor, using a crane. After that, the fuel reaches the 0 conveyor, which is equipped with a metal separator to remove metal pieces from the wood chips. The 0 conveyor also has brushes for cleaning wood dust. Then, after the 0 conveyor, the fuel moves to conveyor number one and further to the second conveyor, which in turn drops the fuel into the boiler fuel bunkers. The second conveyor can change its direction to select the required boiler. The bunkers are designed to avoid jams. Each bunker is equipped with two LED elements to determine the maximum (B) and minimum (A) levels in the bunker, can be see in Figure3.1.

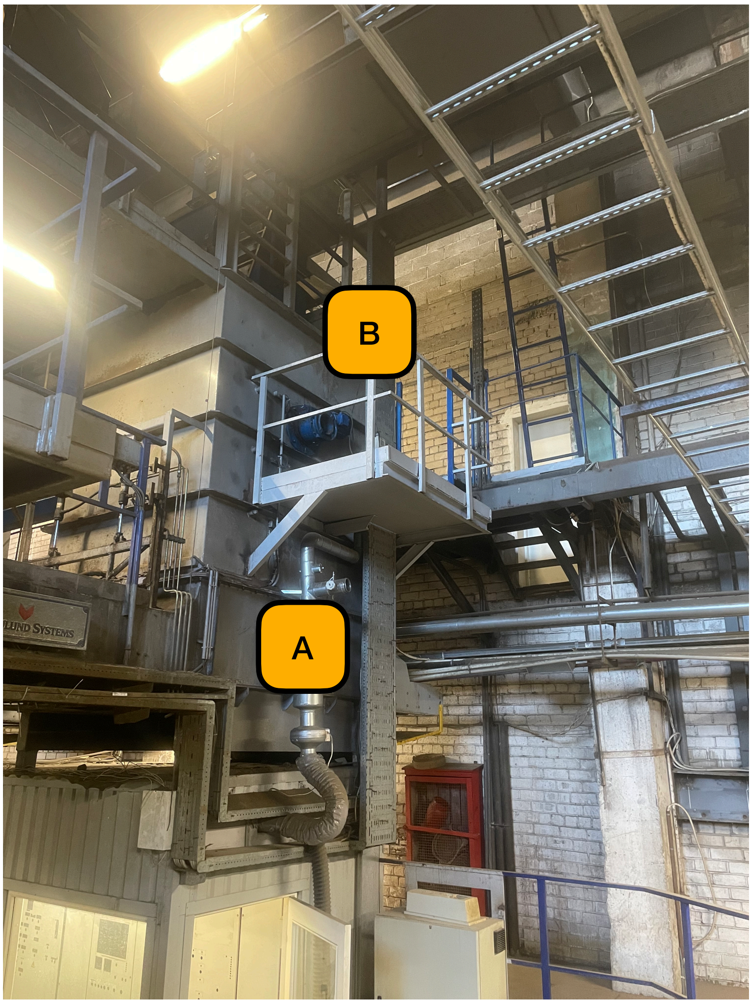


Figure 3.1: Boiler 2 mini-silo

At the bottom of the bunker, there is a feeding table with two feeding pistons powered by hydraulic drives covering the entire width of the grate. The pistons are positioned at the same level as the top of the grate mat. Due to the simultaneous forward movement of the piston, fuel is fed onto the grate mat. An iron comb with a hydraulic drive is inserted into the packed fuel to hold it in place while the pistons retract. The bunker is equipped with a fire protection system to prevent backfires.

3.1.2. Burning

As soon as the fuel is on the grate mat, it is pushed upwards and forward in one motion by the moving fire grates. Continuous mixing is crucial for all types of fuel to ensure that the layer of fuel dries out simultaneously across the entire front. The movement of the grate ensures that there are no areas on the grate where air penetration is excluded. Since the installation must be able to burn fuel with up to 55% water content, hot flue gas at 300°C -400°C is added under the grate to aid the drying process.

The remaining ash and slag are transported to the end of the grate and dropped onto the top of the ash pit, which opens by command after the feeder has operated the number of times specified by the operator.

The same pipe takes primary and secondary air for combustion through the roof. Under the roof, an air intake and a damper are placed, allowing the mixing of cold air with hot air from the boiler room. After the damper, the intake pipe is divided into two parts: one for primary air and another for secondary air.

Primary air for combustion is supplied to a grate form located below. The amount of air is automatically regulated, and the distribution of air is controlled by four manual dampers.

Secondary air for combustion is supplied to the furnace through nozzles located on both sides; the air supply is automatically regulated, and ten manual dampers control the air distribution.

3.1.3. Exhaust system

After leaving the boiler, the flue gas goes through a multicyclone, reducing the particle content to less than 200 mg/Nm³. After the cyclone, the flue gases are moved by a flue gas fan to the chimney. The negative pressure in the boiler is automatically adjusted to the set value using a damper located before the flue gas fan.

3.1.4.Ash remove

Ash and slag from the slag bunker pass through sealed double ash gates into the screw conveyor system, where they are transported to a container. The ash gates consist of 2 sliding doors with hydraulic drives, which are activated one at a time to ensure that unwanted air does not enter the furnace.

A small amount of ash and sand can fall through the grate and is collected in four ash bunkers located under the grate. The ash from these bunkers is sucked up by a small fan and blown through an ash pit, from where it is transported together with the slag to a container.

The ash deposited in the multicyclone is transported to the ash conveyor through a rotary ash pit and goes into a container. The ash and slag enter the container, where they are distributed by a screw conveyor located inside the container.

3.1.5. Water part

Water circulation in the two boilers is provided by 2 water pumps, one pump per boiler. Figure 3.2 shows the principle water part diagram. The outputs of the boilers are connected to the common water supply network through heat exchangers. The flow system is equipped with a bypass function, ensuring a minimum return temperature of 80°C back to the boiler. Automatic pressure maintenance systems maintain the pressure in the systems.

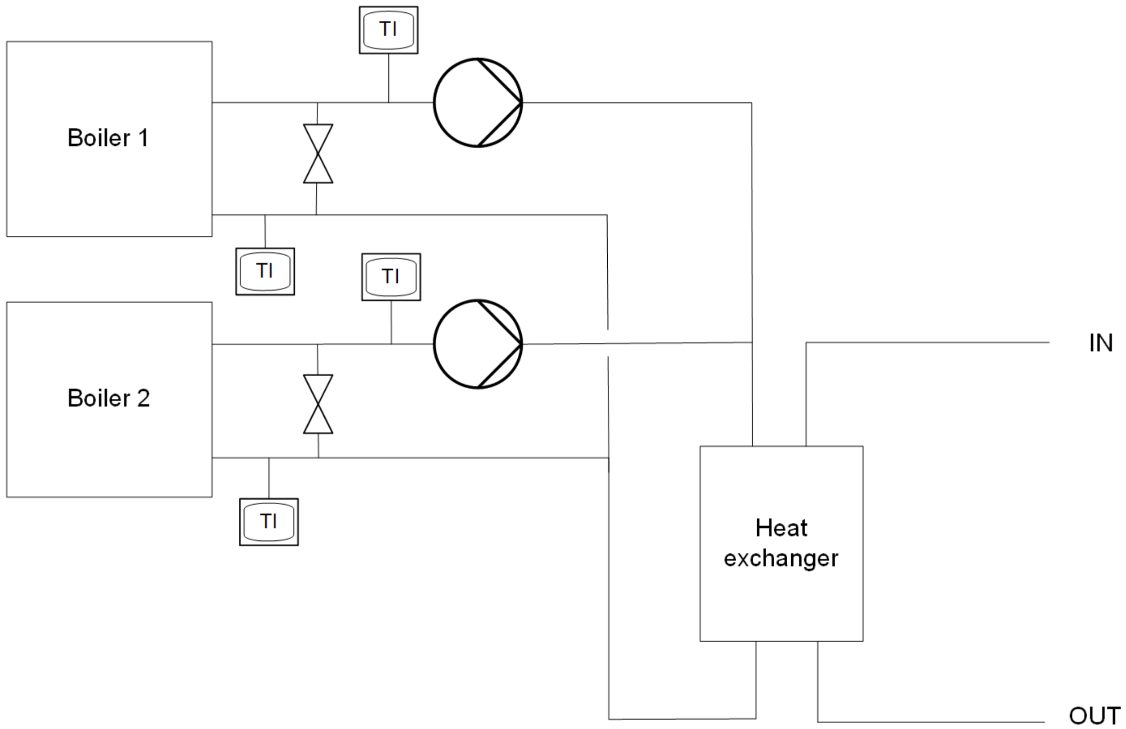


Figure 3.2: Principle water part diagram

3.1.6. Obsolete system control

Control cabinets are divided into two sections, see Figure 3.3, the power supply section and the control section, which are electrically connected through numerous cables and terminal connections. Also, the power supply is divided into two groups: 230 volts alternating current and 24 volts direct current. All low-voltage wires are connected to the control section, and all 400/230V AC cables are to the power supply section. All cabinets are interconnected but separated by steel plates. The power supply section and the control section are further divided into boiler 1, boiler 2, and a common part, each part having its separate cable field.

The control system consisted of 3 PLCs, Allan Bradley SLC5/03 CPU, one PLC for each boiler and one for the general system. All three PLCs are interconnected and support communication among each other. The control interface is located on the doors of the cabinets and consists of a display and mechanical switches integrated into the control system.

The alarm system is implemented on the display in the form of a list of active signals, and some signals are brought out to the doors of the cabinets using indicator lights. If a signal has a reset button, the signal must first be acknowledged on the display and then reset by pressing the button on the front of the cabinet. Suppose group control or a component is disabled due to a fault in the thermal relay after rectifying the thermal relay fault. In that case, the group control or component needs to be reconnected. This means that the alarm signal must be reset, the motor's protective switch reset, and the motor restarted from the front panel or the operator's screen if the motor was disabled due to a thermal fault.

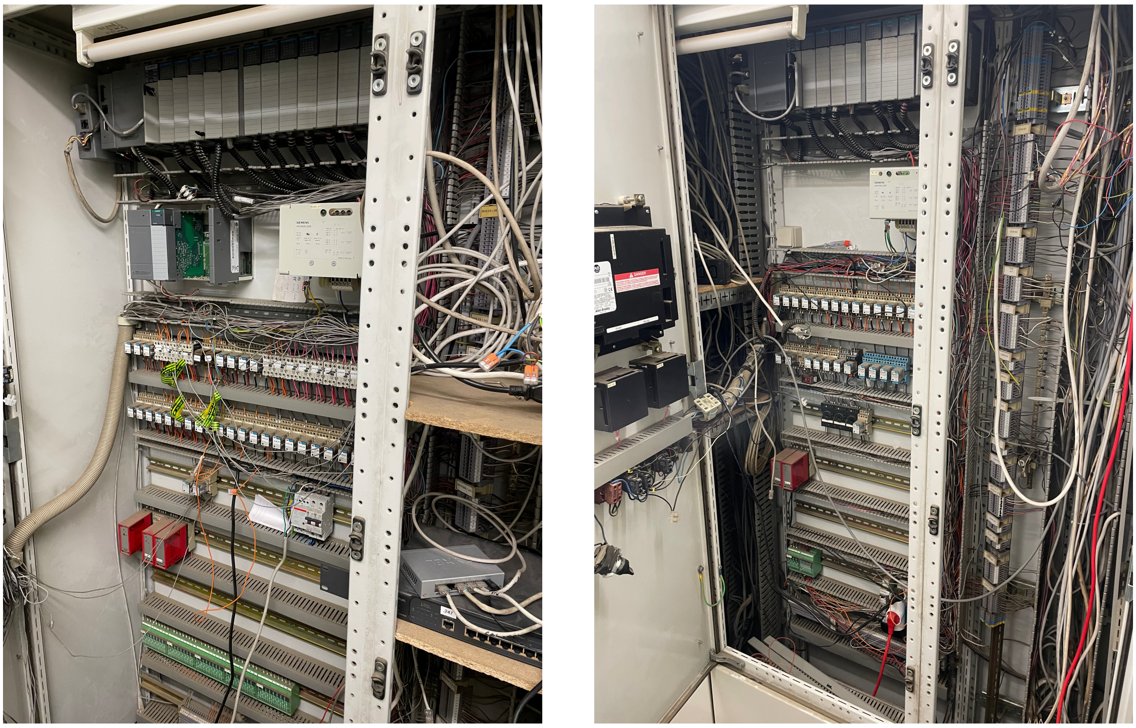


Figure 3.3: Boiler 1 and common cabinets

4. IMPLEMENTATION CONTROL SYSTEM

The purpose of this paragraph is to describe the work that has been done.

4.1.Client requirements and preference

The project was prepared by the contractor based on the technical specifications provided by the client. During the project's execution, both parties made changes by mutual agreement, with the foundation being the experience gained during previous projects. The objectives set by the client for the contractor were:

- Modernisation of the existing automation system: partial updating of sensors, wires, cabinets, controllers, input/output cards, power systems, and communication modules; transferring and modernising control programs; and replacing relay logic with software logic.
- Connecting the boiler room to the client's existing industrial network. Providing control from local devices (tablet, computer) as well as remotely from the central station's console.
- Updating the boiler protection system (obtaining a certificate) and implementing the use of the equipment marking system according to the German standard (Kraftwerk Kennzeichnen System / Identification Systems for Power Plants).
- Training of personnel.
- Equipment startup and commissioning.

The first step was to create a general system diagram showing the necessary equipment and system topology. The diagram was changed several times during the project as previously unknown circumstances were revealed. Figure 4.1 shows the final diagram; as the project was much larger than described in this work, the diagram is somewhat more extensive.

1. Customer Network: The connection point for the new network into the existing one via CAT6 cable.
2. Industrial switch level 2: Provides redundant communication between the local and main networks.
3. Boiler 1: An automation cabinet where all necessary components are located
   3.1.ACN MR: Industrial redundant mini-computers on which the necessary programs are executed.
   3.2.Transitions of comm: From current loops to Ethernet
   3.3.Siemens Profibus terminator - a terminating resistor. Ensures the correct operation of PROFIBUS lines by preventing signal reflection.
   3.4.Industrial switch level 2: Provides communication between remote I/O cards.
   3.5.Optical boxes: The connection point for optical cables.
   3.6. IO cards, allow communication between field devices and DCS.
4. Boiler 2: An automation cabinet where automation equipment is located

4.1. Remote I/O cards: Provide communication between field devices and the automation system.

5. Common system: An automation cabinet where automation equipment is located

   5.1. Optical link module (OLM) - converts the electrical signal and allows the creation of a network ring, thereby providing increased fault tolerance of the control system.

   5.2. Remote I/O cards: Provide communication between field devices and the automation system.

6. The operator station allows for monitoring, managing, and analysing the system.

   Back-Up - storage with all necessary files for the automatic startup of the system

   Alarm station - software for collecting and tracking alarms and emergency signals.

7. Portable operator station: This allows monitoring, managing, and analyzing the system from any point within the boiler plant territory.

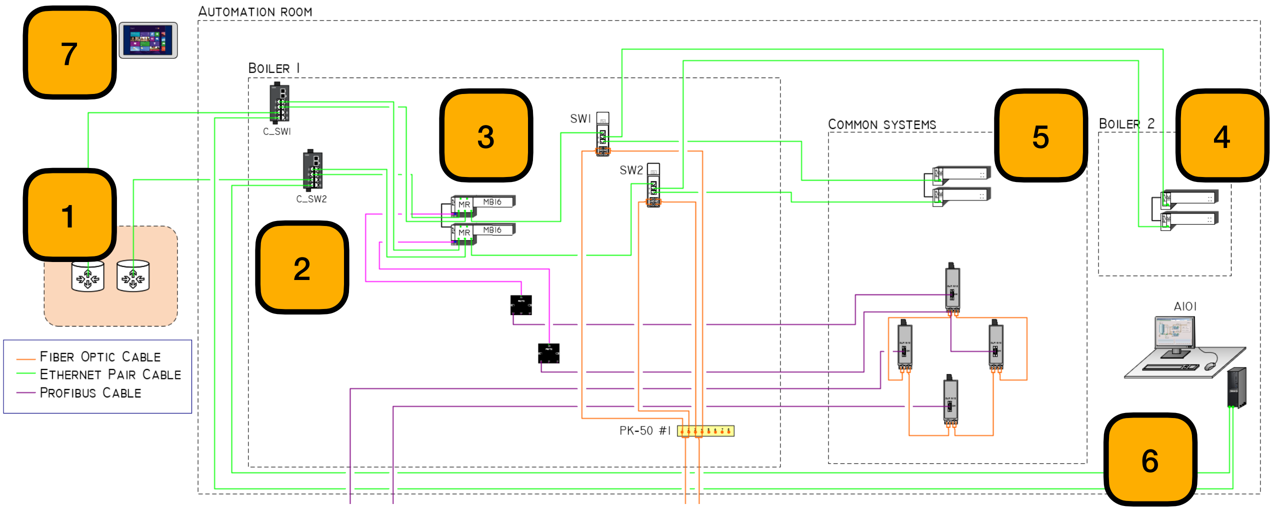


Figure 4.1: System layout

4.2 Control logic and diagrams

Together with the client's technologists, a principal control model was developed, showing the dependencies between components. The diagram changed many times during the project. It's important to note that such a principal diagram requires a precise understanding of the system's operation. This diagram provides a valuable tool for technical specialists servicing and managing the equipment, allowing them to easily identify and configure system components. Figure 4.2 presents a part of the control diagram, illustrating the key logic elements and main device components. When creating such diagrams, it is crucial to maintain balance, avoiding excessive complexity and overload. The full version of the diagram is available in Appendix 1.

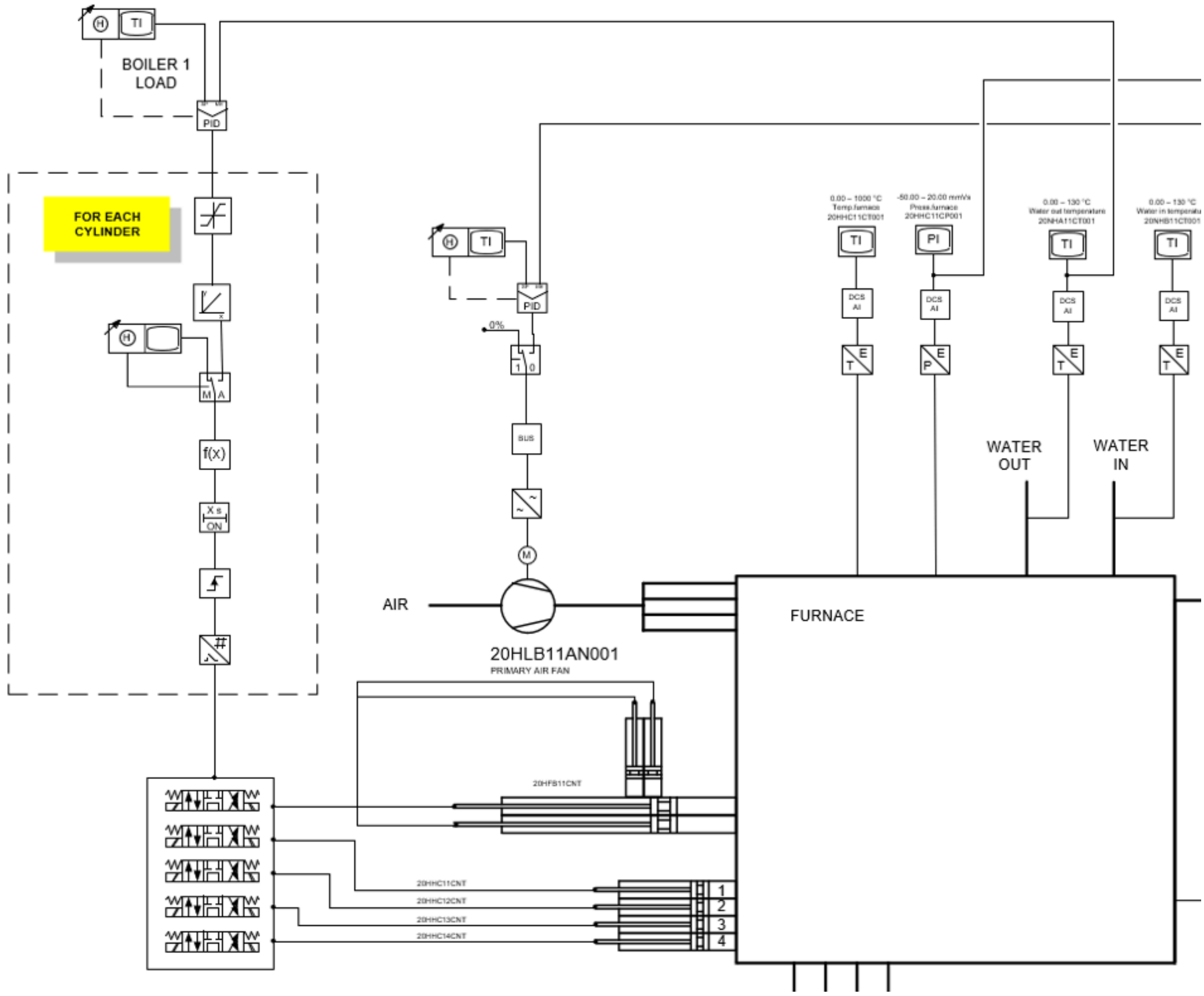


Figure 4.2: Control diagram

4.2.1 Fuel store

During the upgrade, the warehouse was modernised, but the structure and basic shape of the building remained unchanged. To ensure automatic fuel supply, a moving floor and a conveyor at the end of the warehouse were added. The floor consists of a structure at the bottom of the pool, where a special coating performs translational movements, thereby delivering the wood chips from the beginning of the warehouse to the conveyor at the end. The conveyor is located below the floor level, and the wood chips falls onto it by gravity. It is then fed into a shredder, which in turn grinds large pieces of wood or breaks up frozen sawdust. The main advantage of this solution is that delivery trucks can easily unload biomass onto the moving floor, where scrapers transport the material. No staff intervention is required for the operation of such equipment.

To ensure efficient and autonomous delivery of wood chips from the warehouse to the mini-silo, the following equipment is necessary, Figure 4.3:

1. Hydraulic cylinders are used to control the scrapers that move the fuel across the warehouse floor.
2. Hydraulic station: provides the necessary pressure for the operation of hydraulic cylinders.
   2.1. Thermostat: In case of oil overheating, it automatically stops the hydraulic station.
   2.2. Float switch: In case of oil leakage, it stops the operation of the hydraulic station to avoid dry running and equipment breakdown.
   2.3. Solenoid blocks: ensure the direction and pressure of the hydraulic oil.
3. Conveyors: transport fuel from the warehouse to the mini-silo, located between two structures, the warehouse and the boiler house building.

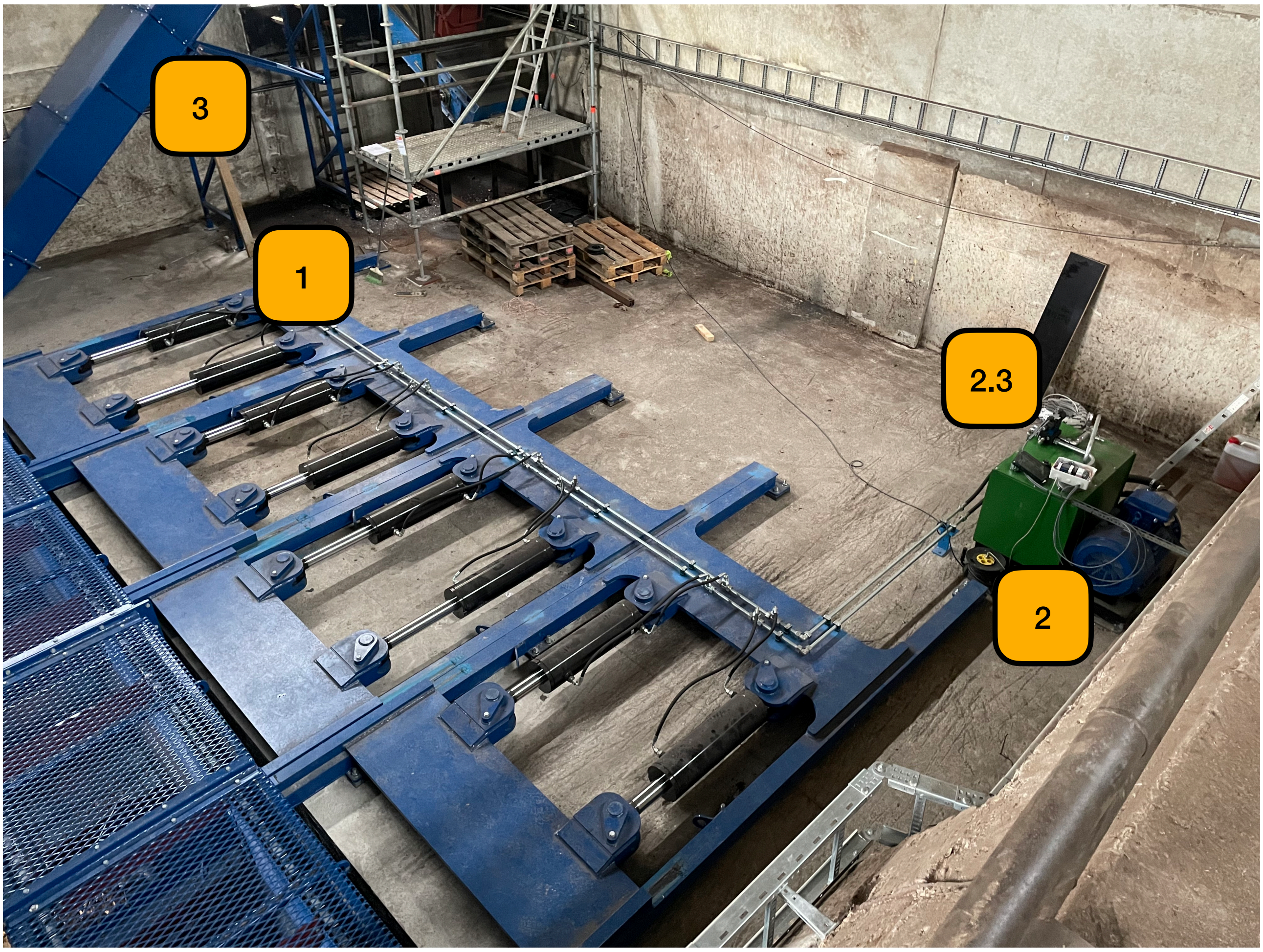


FIGURE 4.3: Fuel store

4. Rotation sensor: indicates that the conveyor has started and is moving.

The repetition seems to be an oversight, so the essential elements for an efficient and autonomous wood chips delivery system include hydraulic cylinders for scraper movement, a hydraulic station for pressure provision, safety devices like a thermostat and float switch to prevent overheating and oil leakage, solenoid blocks for hydraulic oil control, conveyors for fuel transport, and a rotation sensor to monitor conveyor activity.

Hydraulic stations provide the necessary oil pressure for the movement of hydraulic cylinders, which are connected to scrapers. The scrapers pull the biomass onto the conveyor. The hydraulic station is equipped with a low oil level and temperature switch for safety. Manual valves on the pipelines allow for isolating certain hydraulic pistons if necessary (for example, in case of high-pressure hose damage). Solenoid valves enable control over the system's logic for directing pressurised oil to the required part of the hydraulic cylinder. The warehouse management logic depends on the status of the conveyors. The hydraulic station cannot be

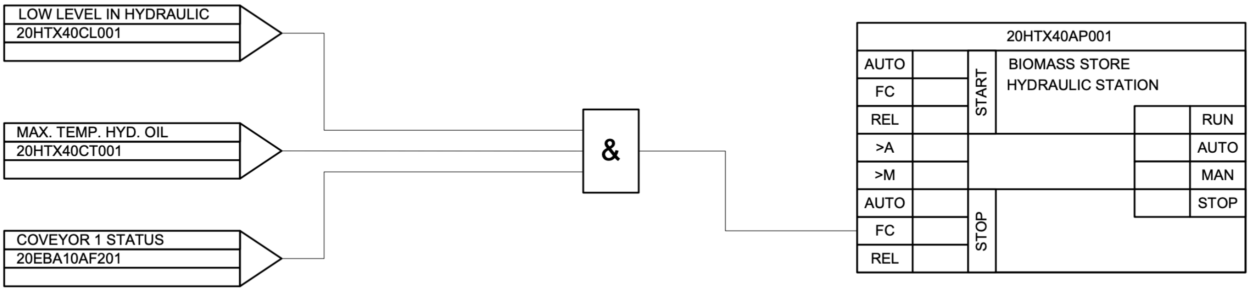


Figure 4.4: Hydraulic station interlocks

started while the conveyors are stopped. The logic diagram for the hydraulic station in Figure 4.4.

Conveyors are started according to the level in the mini-silo. When the mini-silo is filled, the conveyors stop in a predetermined order from the first to the last. Conveyors are started after the fuel pushers have made a specified number of pushes. For safety reasons for both people

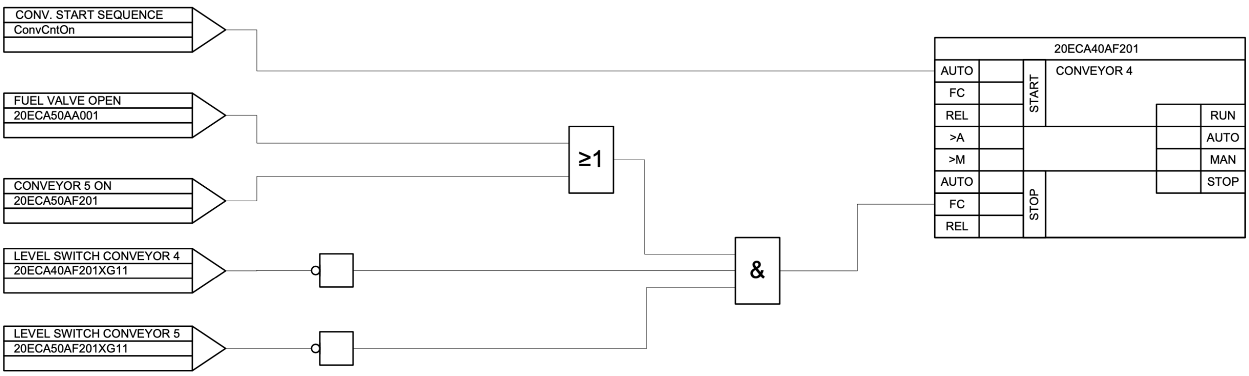


Figure 4.5: Conveyor 4 interlocks

and equipment, multiple interlocks, Figure 4.5, on the conveyors are implemented at different levels. The diagram below shows the interlock signals and the control logic with the MTR block mentioned in the previous paragraph. As an example, the first conveyor is shown, with the remaining ones operating on the same principles.

During normal operation, the hydraulic station cannot be turned on or stopped if a conveyor stops or one emergency relay is triggered. This is done to prevent jams in the fuel supply line as well as to prevent equipment damage. Also, the automation system will stop the operation of the hydraulic pump in two situations: the first is when the temperature relay is triggered, indicating an emergency high oil temperature. In the second case, a drop in the oil level in the oil tank will also stop the operation of the electric motor.

A minimum number of necessary conveyors, Figure 4.6, namely five units, were installed for fuel delivery. Each conveyor is a straight structure along which a chain with attached metal plates moves. To control a single conveyor, the following equipment is necessary:

- An electric motor of suitable power. Needed to drive the chain and the transmission mechanism.
- In case the conveyor jams, a rotation sensor helps avoid overloading the motor or breaking the gearbox.
- A fill sensor, in case of changes or partial failure of equipment, helps to stop the chain movement in a timely manner and avoid mechanical breakdowns. For efficient control,

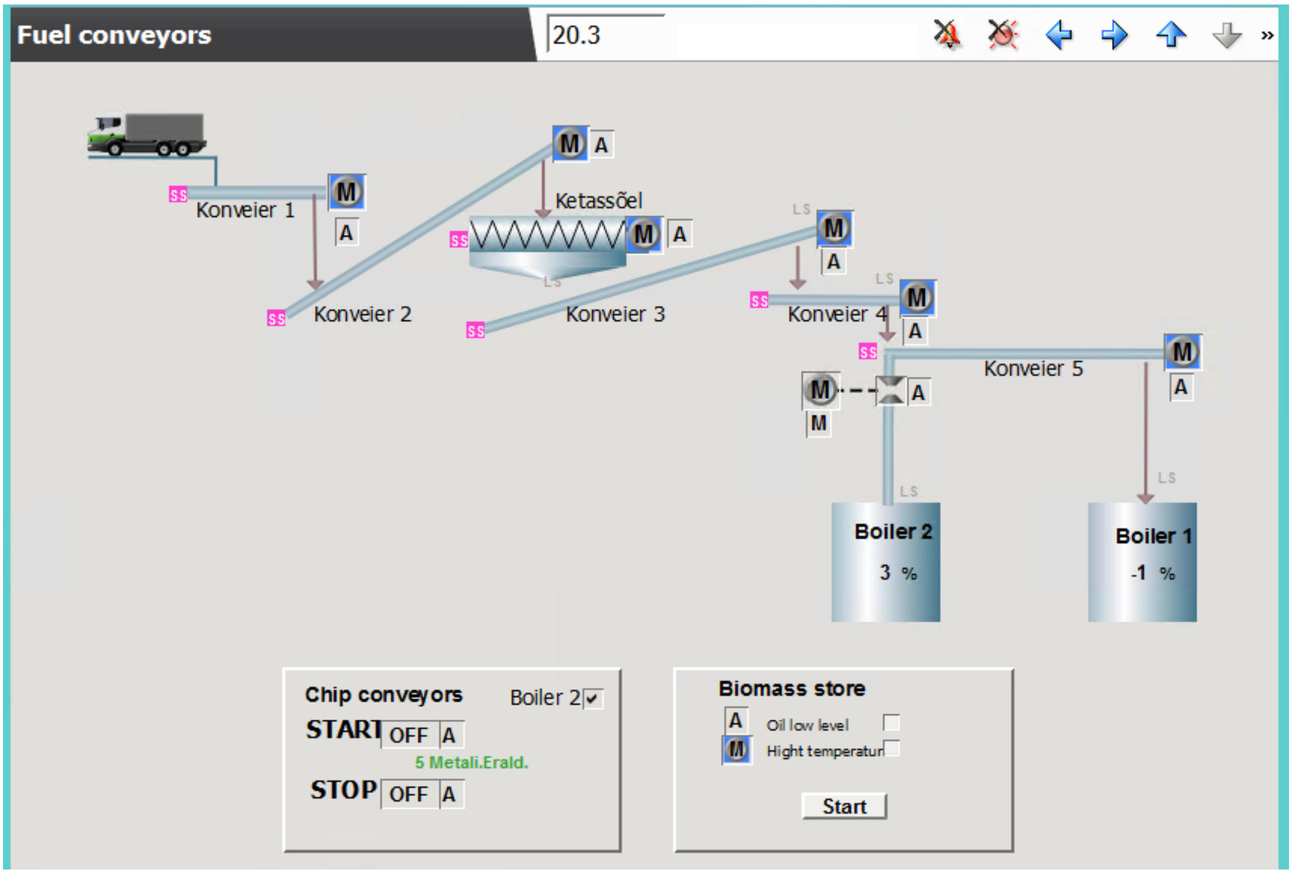


Figure 4.6: Conveyors operation display

protective and control signals were added to each standard control program, as shown in the image above.

4.2.2 Fuel delivery to the furnace

To organise a continuous, even, and smooth delivery of wood chips to the furnace, the following mechanisms are needed:

1. Hydraulic station: creates the necessary pressure in the hydraulic cylinders.
2. 2 hydraulic cylinders: move the pushers.
3. 2 hydraulic cylinders: control the forks.
4. Fire suppression system: prevents fire from spreading to the mini-silo in case of increased temperature in the feeding chamber.
5. Thermostat (in the fuel feeding shaft): monitors the temperature in the feeding chamber.
6. Thermostat: In case of oil overheating, it automatically stops the hydraulic station.
7. Float switch: This switch stops the hydraulic station's operation in case of oil leakage to avoid dry running and equipment damage.
8. Solenoid control blocks: direct the hydraulic oil to the necessary side of the cylinder.
9. Pressure switch: stops the motor in case of cylinder jamming or problems with the oil pipeline, preventing high-pressure pipeline destruction.
10. Level sensors in the mini-silo: necessary for timely stopping the fuel feeding line.

The hydraulic station provides the necessary oil pressure for the movement of the hydraulic cylinders. Control programs choose the direction of cylinder movement by opening/closing the necessary solenoid valves at the hydraulic station, ensuring movement in the required direction.

Fuel is fed into the combustion chamber by two fuel feed cylinders (A) and cut-off forks (B) in a specific order. The forks cut off a portion of the mini-silo and prevent the chips from returning. The fuel feeding rate is set by the operator or calculated by the control program depending on the set load, taking into account corrections for fuel moisture. Corrections are entered into special tables and can be changed by the operator at any time, Figure 4.7.

One push cycle is considered a complete rotation of the cylinder from its starting position back to the starting point. A detailed description follows:

Step 1: From the starting position, with the cylinder outside, start pushing it inside.
Step 2: Lower the cut-off forks down when the cylinder is inside.
Step 3: At the moment the forks reach the bottom position, start moving the cylinder back.
Step 4: Upon reaching the pusher outside, raise the forks up.

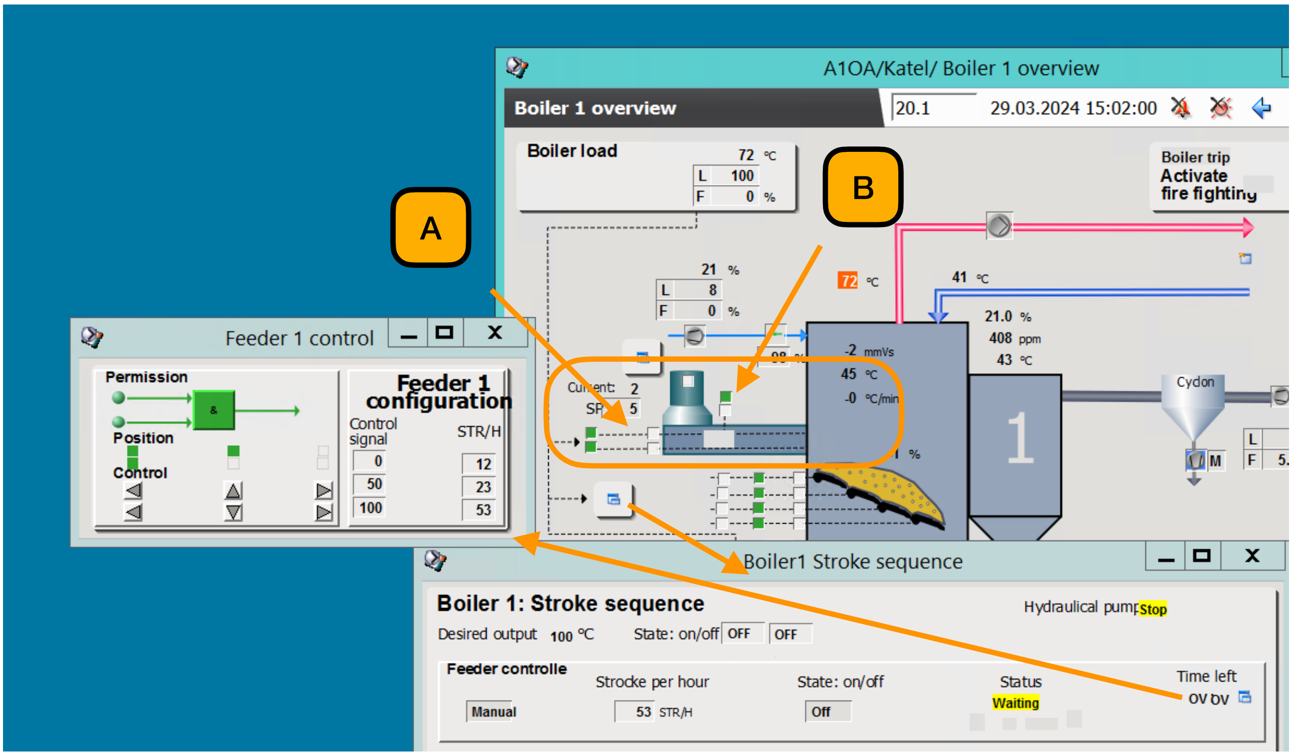


Figure 4.7: Feeders control operation display

4.2.3 Combustion

Optimal combustion in the furnace is achieved by finely adjusting a multitude of dependent parameters that influence the temperature and oxygen content in the combustion zone. To reach the necessary control values, management is executed by supplying primary and secondary air, adjusting the fuel feed rate, and the frequency of movement of the grates. The principle diagram below illustrates this setup.

To achieve the desired system output, all input parameters of the combustion zone must be monitored. The required equipment and control logic are described further in Figure 4.8.

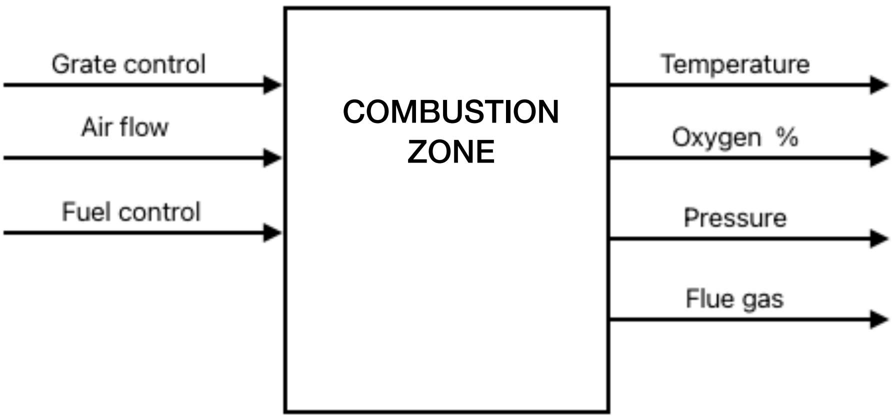


Figure 4.8: Basic Control Scheme for Biomass Combustion Process

The previous paragraph described equipment and methods for controlling fuel supply. As described previously, the fuel feed rate is implemented through a linked table. However, this solution has some drawbacks. If the fuel quality changes significantly, the linked table will provide inaccurate control over the fuel feed rate. The responsible person must clearly understand which parameters and coefficients should be used; determining these coefficients within the scope of this work is not feasible.

To implement air introduction into the combustion zone, the following equipment is necessary:

- 1. Primary Air Fan: Supplies the air needed to initiate combustion.
- 2. Secondary Air Fan: This fan supplies air above the grates to maintain combustion in a specific zone of the furnace.
- 3. Oxygen Content Sensor in Flue Gases: This sensor allows for adjusting the rotation speed of the secondary fan's motor to ensure a sufficient volume of air.
- 4. Manual Valves for Primary Air Adjustment: Allow for distributing the air volume across the entire volume of wood chips.
- 5. Manual Valves for Secondary Air Adjustment: Allow for distributing air supply across zones to achieve longer combustion at lower temperatures.
- 6. Temperature Sensor on the Outlet Water: Participates in calculating the power extracted from the boiler.

The distribution valves for primary and secondary air within the furnace are mechanically controlled by the operator on-site. The operator can control which combustion area receives more air. This allows the operator to specify where in the furnace combustion occurs, enabling precise control over the combustion process to optimise efficiency, ensure complete fuel burning, and adjust to changing conditions within the furnace.

Control of the primary air fan is implemented using a linked table. The load on the fan motor is regulated by a PID controller based on the main PID and the linked table. Primary air is supplied under the grate, thereby supporting combustion, regulating the furnace temperature, and contributing to even burning. The supply of primary air is one of the critical factors for optimising the combustion process and ensuring efficient burning. During the commissioning work, parameters were selected using methods such as Ziegler-Nichols and Cohen-Coon. However, more precise equipment tuning was performed in collaboration with a process engineer using the "trial and error" method, based on the engineer's experience. The following parameters are used:

$$K_C = 1.00$$

$$T_i = 30.00$$

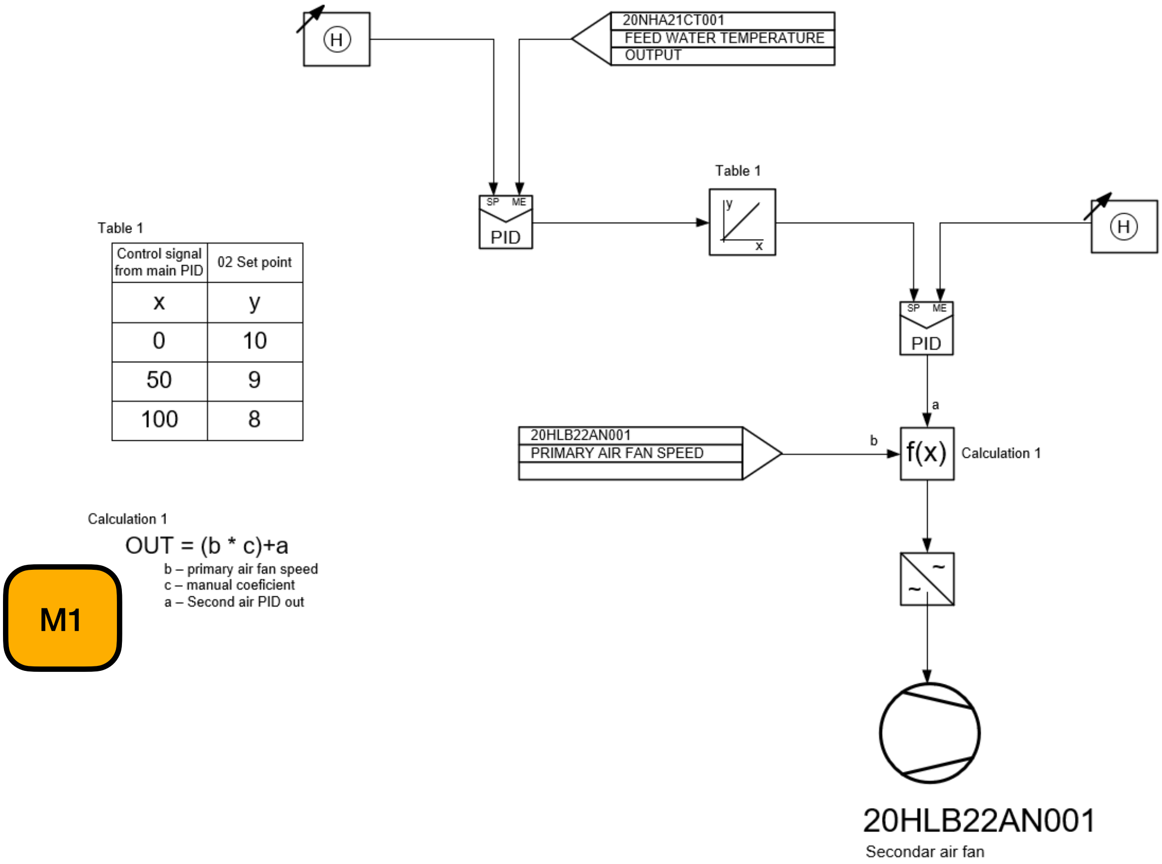


Figure 4.9: Second air control diagram

The flow of secondary air controls the oxygen concentration in flue gases. This allows for the control of parameters such as the completeness of fuel combustion, reduction of harmful emissions, improvement of heat distribution, and temperature control. The control of the secondary air fan is implemented using a mathematical formula (M1), in Figure 4.9, where the input is a control signal from the main PI (Proportional-Integral) controller, and the output is the percentage of oxygen in the furnace.

The PI controller's settings can be changed according to the operator's wishes. The controller has a control minimum output limit of 20%, so if the oxygen level is above the set value, the controller cannot provide a zero output (0%) for the fan motor. This ensures that the air necessary for combustion is always supplied. In this case, there was an attempt to use the Cohen-Coon method. However, due to the high variability of the fuel and factors such as humidity, as the tuning was conducted during the off-season, the attempts did not yield the necessary results. Consequently, the parameters were selected using the trial and error method, based on the knowledge of the operating staff.

$$K_C = 0.75$$

$$T_i = 100$$

Wood chips are burned in the furnace, descending through the grate from top to bottom. Upon reaching the bottom part of the furnace, only ash remains, which is removed from the furnace through hatches at the bottom. The equipment necessary to implement the movement of the grates includes:

- 1. Hydraulic Station (the same one used for organising the movement of pushers): It provides the necessary hydraulic pressure to operate the system.
- 2. 4 Hydraulic Cylinders, one for each section of the grate: These cylinders control the movement of the grate sections to ensure even distribution and burning of the wood chips.
- 3. 3 Limit Switches for each hydraulic piston (outside, inside, middle position): These switches are used to control the position of the hydraulic pistons, ensuring precise movement and positioning of the grate sections.
- 4. 3 Solenoid Valves for each cylinder: These valves control the flow of hydraulic fluid to and from the hydraulic cylinders, enabling the precise control of grate movement based on the combustion needs.

The moving grate is divided into four groups. Each group has its own hydraulic cylinder, which is controlled by three solenoid valves and three position sensors. The solenoid valves control the direction of movement of the hydraulic cylinder. The control logic is designed in such a way that each section can be controlled separately from the others, with a frequency set manually or received from the general PI controller through a correction table.

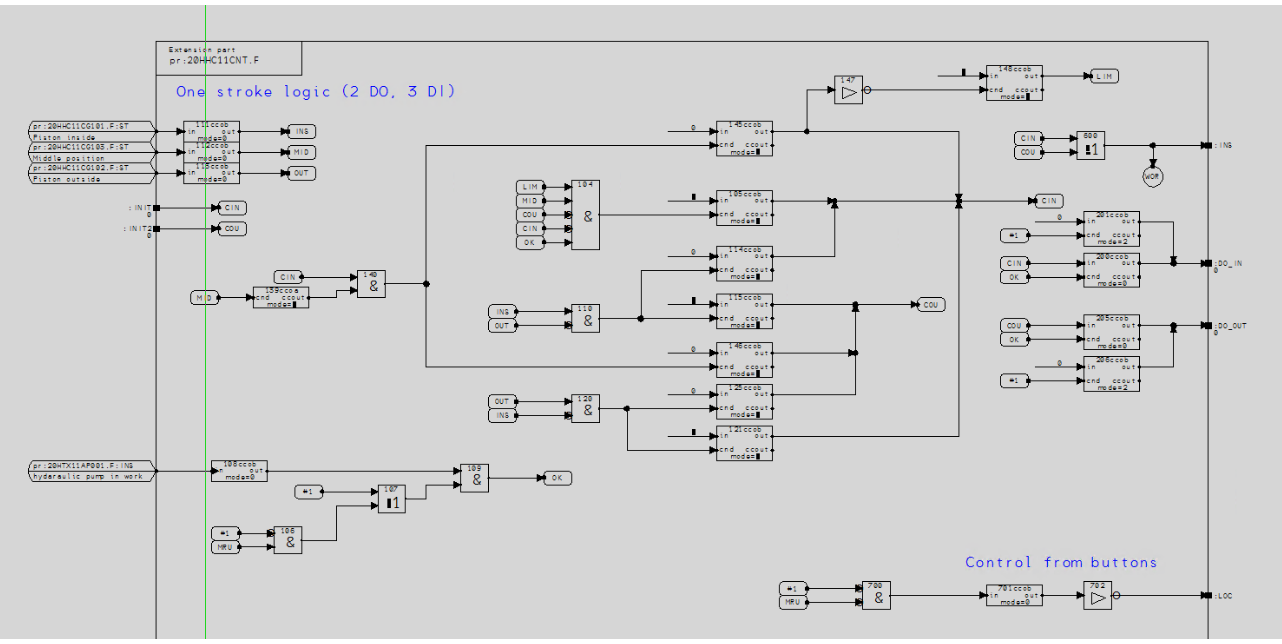


Figure 4.10 Grate logic control

The control logic for the grate movement cylinders is presented in Figure 4.10. Each cylinder operates under its own program, allowing it to be configured individually and independently of the others.

It was decided to regulate the volume of primary and secondary air by changing the electric motor's rotation frequency rather than the damper's position.

4.2.4 Exhaust system

Flue gases are the product of combustion in the furnace. They contain a small percentage of various pollutants, such as particulate matter, carbon monoxide, nitrogen oxides, and sulfur oxides. To reduce environmental pollution, all flue gases are directed through a pipeline to dust collectors for the particulate matter sedimentation process. The following equipment is required for this:

- Furnace draft sensor (pressure sensor)
- Flue gas fan
- Centrifugal flue gas cleaner (cyclone)
- Temperature sensor

A programmable PI controller controls the flue gas fan. The flue gas fan must maintain the pressure in the furnace set by the operator, but it usually is XX to prevent flue gas leaks within the boiler room. Based on the furnace pressure sensor readings, the parameters of the PI controller are presented below. During the startup and commissioning work, parameters were initially selected using methods such as Ziegler-Nichols. However, more precise adjustments were made in collaboration with the process engineer using the "trial and error" method, based on the engineer's experience. The following parameters are used:

$$K_C = 0.75$$
$$T_i = 90.00$$

Exhaust gases are directed through a pipeline to a centrifugal cleaner. Here, the gas is fed into the top of the structure. Dust collection and gas cleaning occur under the action of centrifugal force arising when the gas moves between the housing and the exhaust cone. Captured dust falls into a hopper, and the cleaned gas is expelled through the exhaust pipe into the atmosphere.

During the boiler room update works, the damper in front of the flue gas fan was dismantled, and the adjustment of the draft is now performed using an ABB frequency converter. This approach has proven to be more reliable and less costly than using a large-diameter mechanical gate valve.

During the reconstruction, the client decided to abandon the recuperation of exhaust gases.

4.2.5 Ash remove

The ash formed during combustion falls under the grate by gravity or is delivered to the end of the furnace by the movement of the grate. Ash removal from the furnace is carried out through special mini bunkers to a screw conveyor located under the boiler. Screw motors collect the ash and transport it out of the combustion chamber to the ash conveyor. Screw conveyors take the ash out of the boiler room to a specialised container. Another screw installed under the conveyor cover is used for even distribution of ash inside the container, see Figure 4.11.

Equipment required to be controlled to deliver the ash to the container includes:

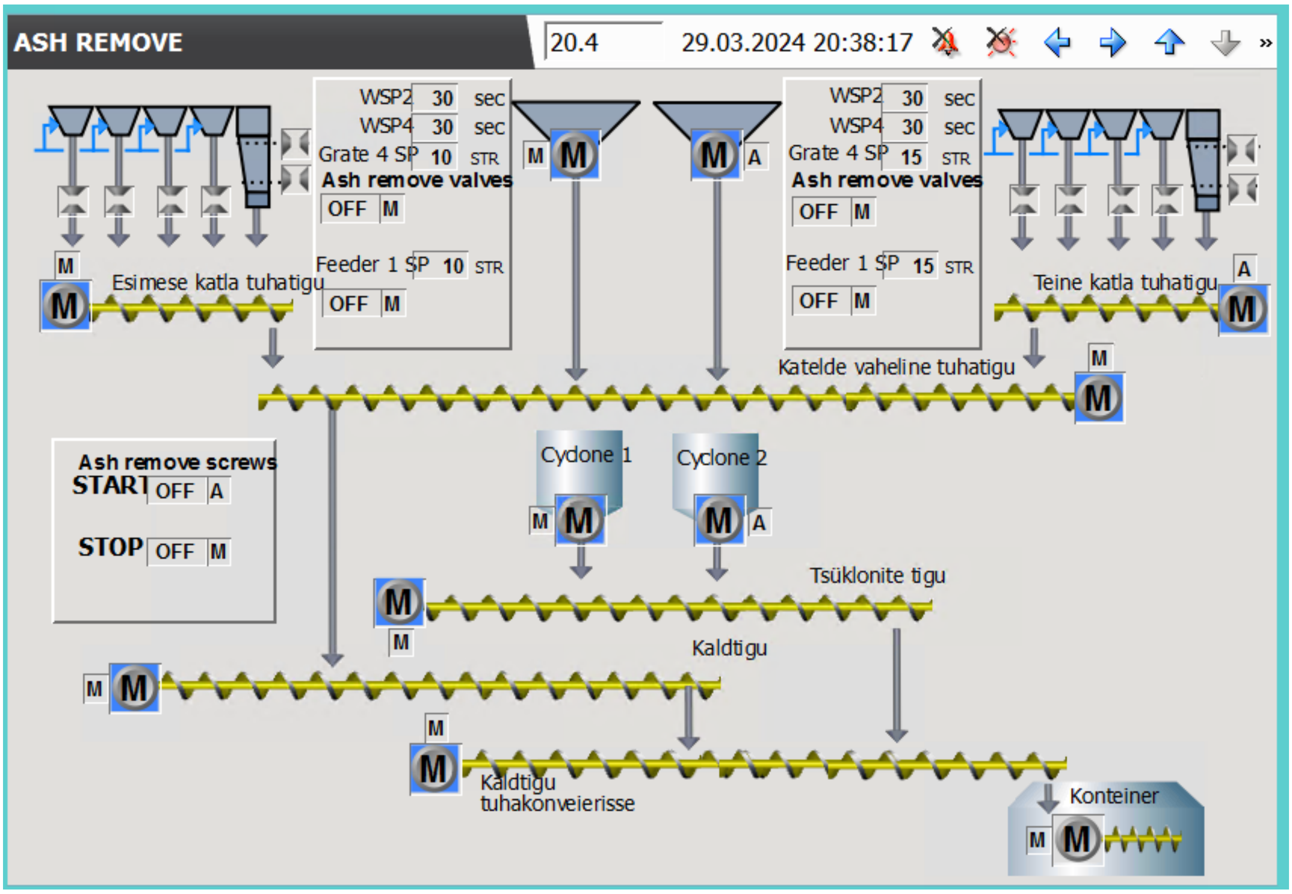


Figure 4.11: Ash remove operator display

- Screw conveyors, 5 units
- Pneumatic valves, 4 units
- Hydraulic valves, 2 units

- Rotation sensors
- Load sensors

The conveyors operate continuously during the boiler's operation. The diagram shows the logical connection between the conveyors:

During the reconstruction, it was decided to replace the small fan, which blew ash from under the grate bunkers, with pneumatic valves that, when opened, dump the ash onto the screw conveyor located under the boiler.

4.2.6 Water part

The water part is located above the furnace. The combustion process generates heat, which is transferred to the water inside the boiler. If the water remained stationary, it would overheat and boil, potentially damaging the boiler. To correctly manage the boiler and distribute the generated heat within the heat exchanger, the following equipment is necessary:

- Temperature sensor for outgoing water
- Temperature sensor for incoming water
- Pressure sensor on the outlet side
- Pressure sensor on the inlet side
- Circulation pump
- Bypass valve
- Dry running sensor

The pump used in the system is designed to operate at a consistent speed, ensuring a steady volume of feedwater is supplied through the internal heat exchanger of the boiler. This ensures continual heat uptake and efficient operation of the boiler system.

To ensure the safe operation of the equipment, the outlet pipe is equipped with two emergency sensors, namely a temperature sensor and a dry run sensor. These sensors are usually closed relays that are activated in case of an emergency.

If any of the sensors are triggered, the emergency power supply system (SRS) immediately disconnects, resulting in the immediate shutdown of both the pump and the entire boiler. This safety mechanism is put in place to prevent any potential damage to the equipment and to maintain safe operation.

Moreover, in case of an emergency, the operator is warned with alarm signals and color-coded warnings to take necessary action. These safety features ensure that the pump and the boiler operate safely and efficiently.

A software-based PI controller controls the water bypass valve. The PI controller receives input measurements from the temperature sensor at the boiler inlet. The active setpoint for the valve is determined by the operator, typically set at 80 degrees Celsius.

During the startup and commissioning work, parameters were initially selected using methods such as the Cohen-Coon Method. However, more precise adjustments were made in collaboration with the process engineer using the "trial and error" method, based on the engineer's experience. The following parameters are used:

$$K_C = 0{,}20$$

$$T_i = 10{,}00$$

CONCLUSION

The goal of this master's thesis was to design and implement a control system for two biomass boilers. The second goal involved developing and tuning software-based PI controllers. At the beginning of the work, a brief overview of possible biomass combustion methods and the technical characteristics of these systems was presented. A review of DCS systems was then conducted using Valmet Automation equipment to familiarise the reader with the engineering tools available for project implementation.

The control programs for the equipment were developed and implemented in collaboration with the client. Based on the author's analysis, continuous on-site interaction with the client and field engineers is considered the most effective method for implementing the project when upgrading outdated equipment. This approach ensures a comprehensive understanding of the system's technology, which is crucial for a successful project outcome.

The tests conducted on the actual boilers have demonstrated their operational, control, and monitoring capabilities across the full range of power, while ensuring that all process parameters remain within the required range. These tests have confirmed that the boilers are capable of performing optimally under varying conditions, exhibiting consistency and reliability in their performance. The results of these tests have provided valuable insights into the operational characteristics of the boilers, which are essential for ensuring their safe and efficient use in industrial settings.

During project implementation author conducted the following activities:

- Automation system design
- Control applications design
- Equipment installation
- Test and calibration of various sensors, like oxygen content sensors, temperature sensors, light sensors, position sensors, etc
- PROFIBUS communication setup and test
- Documentation and preparation of all necessary documents, drawings, descriptions and IO tables
- Communication and clarification of the technological subtleties of the process with staff

REFERENCES

[1]Pärnu elanike arv suurenes 923 inimese võrra. [*Online*]
https://parnu.ee/uudised/uudised-koik/5538-paernu-elanike-arv-suurenes-923-inimese-vorra.
Accessed on: February 20, 2024.

[2]Statistikaamet, Ehitus. [*Online*]
https://www.stat.ee/et/avasta-statistikat/valdkonnad/majandus/ehitus.
Accessed on: February 20, 2024.

[3]Trading Economics, EU Natural Gas. [*Online*]
https://tradingeconomics.com/commodity/eu-natural-gas.
Accessed on: January 24, 2024.

[4]European Commission, European Climate Law. [*Online*]
https://climate.ec.europa.eu/eu-action/european-climate-law_en
Accessed on: April 14, 2024.

[5]World Resources Institute, Sustainable Biomass and Carbon Removal. [*Online*]
https://www.wri.org/insights/sustainable-biomass-carbon-removal
Accessed on: January 28, 2024.

[6]World Bioenergy Association, Global bioenergy statistics 2022.

[7]V. Tzelepi et al., "Biomass Availability in Europe as an Alternative Fuel for Full Conversion of Lignite Power Plants," A Critical Review: Energies, 2020, https://doi.org/10.3390/en13133390.

[8]M. Santolini, C. Ellinas, and C. Nicolaides, "Uncovering the fragility of large-scale engineering projects," EPJ Data Science, vol. 10, pp. 1-13, 2020, https://doi.org/10.1140/epjds/s13688-021-00291-w.

[9]The Evolution of Heating: Tracing the Fascinating History of Boilers: History of Yesterday, [*Online*]
https://historyofyesterday.com/the-evolution-of-heating-tracing-the-fascinating-history-of-boilers/.
Accessed on: April 16, 2023.

[10]T. Editors of Encyclopaedia Britannica, Thomas Savery: Encyclopaedia Britannica, April 5, 2024, [*Online*]
https://www.britannica.com/biography/Thomas-Savery.
Accessed on: April 16, 2023.

[11]T. Editors of Encyclopaedia Britannica, Biomass: Encyclopaedia Britannica, March 15, 2024, [*Online*]
https://www.britannica.com/science/biomass.
Accessed on: April 16, 2023.

[12]R. Collado et al., "Almond Shells and Exhausted Olive Cake as Fuels for Biomass Domestic Boilers: Optimization, Performance and Pollutant Emissions," Sustainability, 2022, https://doi.org/10.3390/su14127271.

[13]F. Cherubini et al., "CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming," GCB Bioenergy, vol. 3, 2011, https://doi.org/10.1111/j.1757-1707.2011.01102.x.

[14]M. Meiller et al., "Development of a New Sensor Module for an Enhanced Fuel Flexible Operation of Biomass Boilers," Processes, vol. 9, 661, 2021, https://doi.org/10.3390/PR9040661.

[15]Statistic Estonia, Forest 2022. [*Online*]
https://www.stat.ee/en/find-statistics/statistics-theme/environment/forest
Accessed on: February 21, 2024.

[16]V. Tzelepi et al., Biomass Availability in Europe as an Alternative Fuel for Full Conversion of Lignite Power Plants: A Critical Review," Energies, 2020, https://doi.org/10.3390/en13133390.

[17]F. Weschenfelder et al., "A review on the complementarity between grid-connected solar and wind power systems," Journal of Cleaner Production, vol. 257, 120617, 2020, https://doi.org/10.1016/j.jclepro.2020.120617.

[18]F. Kanwal et al., Co-Combustion of Blends of Coal and Underutilised Biomass Residues for Environmental Friendly Electrical Energy Production," Sustainability, vol. 13, 4881, 2021, https://doi.org/10.3390/SU13094881.

[19]J. Cordier et al., "The relationship between elemental composition and heat of combustion of microbial biomass," Applied Microbiology and Biotechnology, vol. 25, pp. 305-312, 2004, https://doi.org/10.1007/BF00252538.

[20]J. Simmie, "Detailed chemical kinetic models for the combustion of hydrocarbon fuels:," Progress in Energy and Combustion Science, vol. 29, pp. 599-634, 2003, https://doi.org/10.1016/S0360-1285(03)00060-1.

[21]IEA-ETSAP and IRENA, "Technology Brief E05 – January 2015: Biomass for Heat and Power."

[22]L. Rosendahl, "Biomass combustion science, technology and engineering," 2013.

[23]C. Yin, L. Rosendahl, and S. Kær, "Grate-firing of biomass for heat and power production," Progress in Energy and Combustion Science, vol. 34, pp. 725-754, 2008, https://doi.org/10.1016/J.PECS.2008.05.002.

[24]T. Fouilland, J. Grace, and N. Ellis, "Recent advances in fluidized bed technology in biomass processes," Biofuels, vol. 1, pp. 409-433, 2010, https://doi.org/10.4155/bfs.10.20.

[25]S. Mehmood, B. V. Reddy, and M. A. Rosen, Energy Analysis of a Biomass Co-firing Based Pulverized Coal Power Generation System," 2012.

[26]Y. Xu, K. Yang, J. Zhou, and G. Zhao, "Coal-Biomass Co-Firing Power Generation Technology: Current Status, Challenges and Policy Implications," 2020.

[27]X. Ge, F. Yang, and Q. Han, "Distributed networked control systems: A brief overview" Inf. Sci., vol. 380, pp. 117-131, 2017, https://doi.org/10.1016/j.ins.2015.07.047.

[28]IEC, "IEC Standards", [*Online*]
https://webstore.iec.ch/publication/4552.\
Accessed on: May 02, 2024

[29]Official Valmet internal presentation for customers, 2017.

[30]Valmet DNA Engineering, "Automation Language, Collection 2017, G5095_EN_03".