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Industrial Electrical Engineering and Automation

Control system for parallel batch mixtures and continuous flows in a chemical process - A preliminary study

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Bachelor Thesis

Control system for parallel batch mixtures and continuous flows in chemical process.

- **A preliminary study**

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Abstract

The purpose of this project was to create a preliminary study for a control system. The control system is to be used in a not yet existing piece of equipment. The control system manages and optimizes a delicate chemical process consisting of parallel batch-mixing with several different continuous flows and outputs. The control systems software was compiled in Mitsubishi GX Works 3, using a combination of Ladder Diagram(LD) and Structured Text(ST). The HMI environment consists of touchscreens and was also Mitsubishi-based and implemented with GT Designer 3. The finished control system contains an automated production control, functions for displaying current values of flows and levels, as well as recipe handling functions, data logging functions and alarm functions. The report also contains suggestions of suitable specific hardware, for example sensors or PLCs, as well as a description of operational requirements of the control system. The study is carried out in close relation with the co-operating company to meet their specific requirements.

Keywords: *Mitsubishi, HMI, AD/DA, GX Works, GT Designer, PLC, GOT2000, control system*

Sammanfattning

Syftet med examensarbetet var att genomföra en förstudie och skapa en förlaga till ett styrsystem. Styrsystemet är tänkt att användas i en än icke existerande maskin. Styrsystemet reglerar och övervakar en kemisk process bestående av parallella satsblandningar, kontinuerliga flöden och ett antal utflöden. Mjukvaran till styrsystemet är skrivet i programmet Mitsubishi GX Works 3 med programmeringsspråken Ladder Diagram(LD), och Structured Text(ST). HMI:n utgörs av pekskärmar från Mitsubishi och är skrivet i GT Designer 3. Det färdigställda styrsystemet innehåller en automatiserad produktionsprocess, funktioner som visar aktuella nivåer och flöden, funktioner för recepthantering, dataloggning och larmfunktioner. Förstudien innehåller också förslag på passande hårdvarukomponenter, exempelvis sensorer och PLC-typ, samt en beskrivning för styrsystemets funktionskrav. Förstudien är genomförd i nära relation med sammarbetsföretaget för att försäkra sig om att deras krav uppnås.

Nyckelord: *Mitsubishi, HMI, AD/DA, GX Works, GT Designer, PLC, GOT2000, styrsystem*

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1 Introduction

The co-operating company operated a prototype machine. The prototype machine’s purpose was to create a product. The product was used for evaluation and testing by the co-operating company and in a later stage approved by external governing bodies. This machine was therefore made simple and straight forward in its design to allow for a small-scale testing environment with only the most necessary functions and overall capabilities.

The company set out to produce a larger machine based on the prototype. This larger machine will be used to produce the product in larger quantities for customer use and therefore requires a control system, higher degree of quality control, increased capacities and higher outputs. The formulation of the control system for this larger machine will be the subject of the thesis.

To simplify in the following sections, the prototype machine will be referred to as the *prototype*. The larger, not yet existing machine, will be referred to as the *LS-machine*, the co-operating company will be referred to as only the *company* and material inputs to the LS-machine will be referred to as *compounds,* if nothing else is stated.

2 Thesis specifications

2.1 Background and problem statement

The company had an ongoing development project which was approaching the next phase, the full-scale implementation of the concept. One part of the development project was product testing, another part was specifying product design and a third, establishing that the use of the product met the rules and regulations of the governing bodies that regulate its usage.

The prototype was being used to provide samples of the product for testing and evaluation. When the testing was completed, a government approval was given, and the planning for construction of the LS-machine began, to take the developed concept to full scale.

At the company, current control systems for other products they sell are being controlled by PLCs´ from Mitsubishi. They provide a flexible platform and is the natural choice for usage in future products due to in-house experience. The prototype uses a variant of Mitsubishi called FX5U and provides the prototype with enough capabilities to perform during the testing phase.

The prototype consists of precision pumps, three-phase motors, one-phase motors, load cells and other type of sensors, containers of varying size, mixers, blenders, hoses, and a control system that runs the machine together with an HMI.

To accommodate the higher output, the LS-machine will have larger overall dimensions than the prototype. However, for both machines, the prototype and the LS-machine, the production process consists of the same separate two production lines, A and B. In turn, these product lines consist of compounds, a1, a2, a3, b1, b2, b3 respectively. The components are mixed together in different specific ways as specified by the operator. These parameters include, for example, mixing time, output flow and target volume. At the end of the product line, fluid A and fluid B are mixed in a proportional relation to create fluid C, i.e., the output is a combination of the two. The output volume of fluid B is large in comparison to the batch volume of fluid A, this makes fluid B continuously available.

Almost all of the components on the prototype as well as on the upcoming LS-machine will be off-the-shelf parts from original equipment manufacturers. One benefit of off-the-shelf components are that it simplifies the construction process and makes the preliminary study easier to grasp in terms of specific hardware or software operational compatibilities, requirements and cost. Parts that are not off-the-shelf components are manufactured by specialized sub-suppliers or other manufacturing companies.

The production process, in the prototype and the LS-machine, is continuous and parallel in the sense that several production stages are happening at the same time and the output of the machine is continuous while operational. The prototype has certain limitations which are all planned for, and known. The reason for its limitations is that the only purpose of the prototype was to test the product. These limitations include: a maximum combined output that does not meet the LS-machine planned performance, a limited quality control system that does not ensure constant quality, absence of recipe- and settings management system as well as absence of an alarm system. The increased output will constitute the largest physical change to the LS-machine, compared to the prototype. This means that for example containers and dimensions of product-transport components within the machine will be physically bigger and in some instances in larger quantity. The other points require only modest physical changes, as in adding sensors. However, all of the changes will require a control system for their ability to function individually, and collectively.

Therefore, the thesis aims was to develop a control system for the LS-machine that could incorporate the listed functions and reuse much of the prototypes control system-logic. The main reason for the LS-machine to be based on the prototype system is that the prototype utilizes a few highly specific and specialized functions regarding the production process, the output of which has been thoroughly tested and approved. It was therefore vital that these processes stayed the same when moving to full scale production.

2.2 Research questions

This thesis developed a new control system for a machine that optimizes parallel batch mixtures and continuous flows in a chemical process. The thesis aimed to answer the following questions:

1. How is recipe handling currently carried out when operating the prototype machine?
2. In what way is it suitable to implement recipe handling for the LS-machine. Also, are there any new methods or functions that could be added or revised regarding recipe handling.
3. What is the current logic and design of the prototypes´ process- and control system?
4. How should the process- and quality control be revised for the LS-machine?

2.3 Thesis scope

- Outline operational requirements for the LS-machines control system.
- Create new control system for the LS-machine by utilizing Mitsubishi software and hardware.
- Suggest compatible hardware and software components for the LS-machine.

The scope was further specified in section 4.3.1, Control system requirements.

During the course of the thesis work it became apparent that simulating the control system was not viable. This was mainly due to that creating a simulation environment was too consuming in time to be done within the scope of the thesis. Also, the only way the thesis would benefit in a major way of a simulation would be if the systems were accurately physically modelled. However, it is of course theoretically possible. This aspect is further discussed in chapter 6, Discussion.

3 The PLC and PLC-programming

3.1 The PLC

PLC is an acronym for Programmable Logic Controller. The PLC, in which the control system will be programmed, was invented in the late 1960´s by the company Bedford Associates on order from GM Hydromatic [1].

The PLC is designed to operate in harsh industrial environments. It replaces analog relay structure and control, and implements it digitally. The implementation is done by the user via digital programming and then uploaded to the PLC [1]. Therefore, replacing an analog relay structure with a PLC makes for an easy transition due to the software adaptability. Today, the PLC is a well-known and proven solution, commonly used in many applications in industrial and manufacturing uses, for example controlling magnetic or pneumatic valves, sensors, electric machines(motor/generator), or contactors [1].

The benefits of using a PLC, compared with an analog relay structure, are as follows [1]:

- Lowering installation cost compared to traditional relay control.
- Lowering update and upgrade costs for facilities utilizing PLCs´.
- Effective utilization of tools for troubleshooting controlling systems digitally.

There are multiple original equipment manufacturers of PLCs, the most established of which, are:

- Schneider Electric SA
- Mitsubishi Electric Corporation
- Siemens AG

3.2 General structure of a PLC control system

This chapter includes a brief technical explanation of how a PLC operates, as well as a description of commonly used programming languages.

3.2.1 Layout

An interconnected system utilizing a PLC consists of the controller unit itself, which is considered to be the central part, along with inputs and outputs to and from components. A generic model of a system utilizing a PLC for control, may look like figure 1.

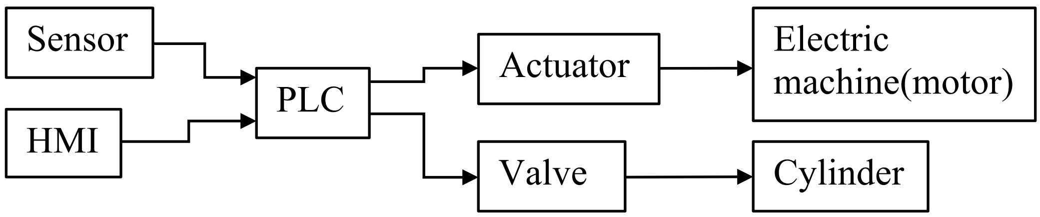


Figure 1, general PLC system

It is common practice to include a feedback function in modern PLC systems, as this increases the precision of system output. In the example shown below, figure 2, the motor speed is fed back vi a sensor to the PLC to give the PLC information about the actual speed of the motor. A set value can then be sent from the PLC to alter the motor speed accordingly.

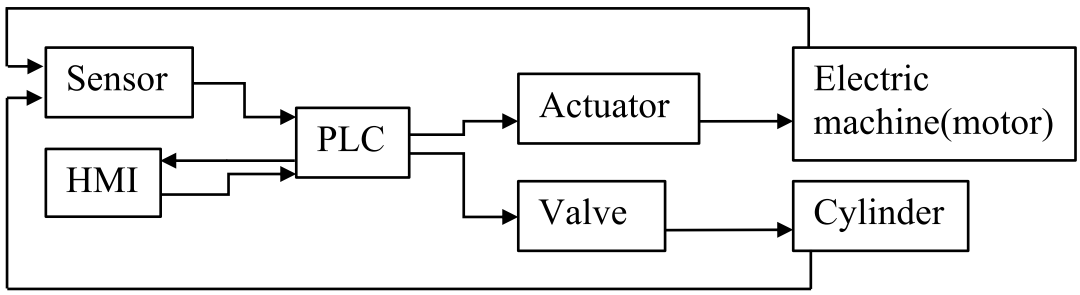


Figure 2, general PLC system with feedback-function

3.2.2 PLC internals, mode of operation, I/O and functions

A PLC is a digital representation of analog relay structure [1]. It utilizes physical inputs and programmable digital outputs to create a system based on logic rules, such as AND, OR, NOT. To make the system easy to comprehend, the input signals can be visually represented in a programming interface as contactors or push buttons. For example, if a push-button is connected to an input of the PLC, it can be represented as a switch in the interface. A motor is usually represented as a coil, and so on. A simple analog relay system can be drawn as follows, figure 3, with A being a relay, K being a contactor and M being a motor. A corresponding system can then be modelled as in figure 4, with X1 being an input in the PLC and Y1 an output, in this case for the motor.

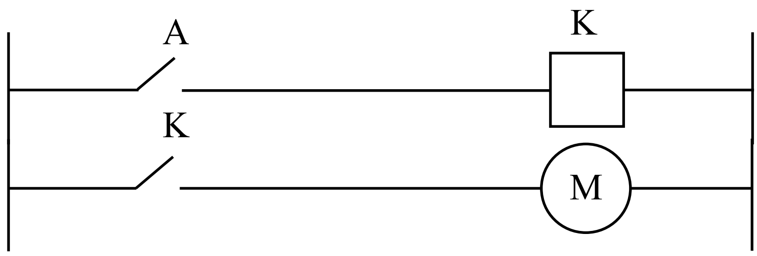


Figure 3, analog relay system

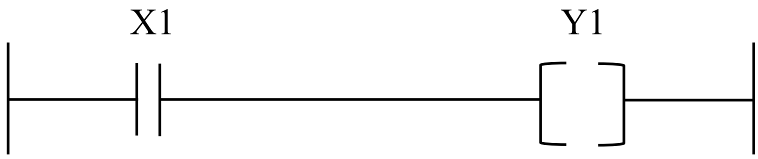


Figure 4, corresponding digital PLC-system

As stated, figure 3 and 4 are very simple, there are for instance no way of making the motor, or Y1, stay on after the button A, or X1, has been pressed. The system requires A, or X1, to be continuously active, or high, for the motor to run. For that, a self-hold function is implemented, an important function PLC-programming. However, if you implement a self-hold function, you also need a way for turning the self-hold function off, that is, the motor in this case. If not, the motor stays on as long as the power is on. Normally there would be an off-function present in an industrial environment, but the point is that you always have to implement the entire function envelope of the modelled physical application, such as the off-button in this case [1].

A typical PLC relies on a number of physical inputs and outputs to fulfil its purpose. The outputs and inputs are referred to as X0, X1, X2… and Y0, Y1, Y2… respectively. The number of input and output slots is often the single largest factor determining the physical size of a PLC.

If the inputs and outputs on the PLC are logical, meaning that they are either on or off, 1 or 0, the typical voltage is often +24 and 0V respectively. If the input or output is used to receive a measured value or to output a specific value within a set range, current between 4 and 20mA is commonly used [9]. With 4mA being 0 and 20mA being the largest value within the specific range of the application.

When receiving or sending specific range values used for measuring or control, an analog to digital, or digital to analog module(AD/DA-module) interface is used [5]. These modules are separate for their respective use, if converting an analog value to a digital, an AD module is used and vice versa. As presented in figure 5, which shows a system utilizing AD and DA modules, handling input and output values respectively.

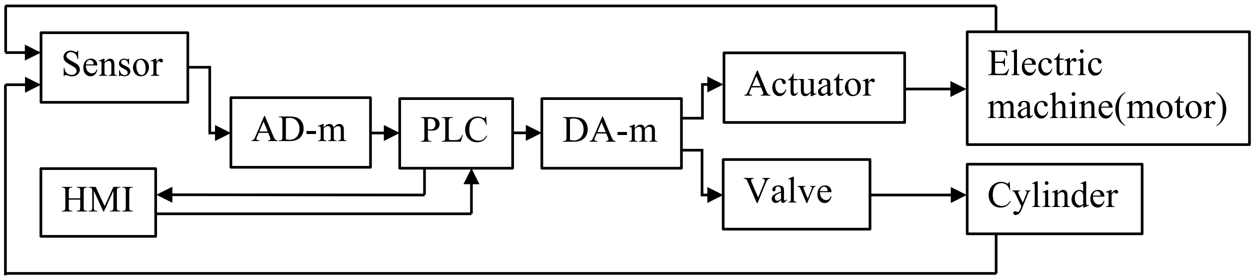


Figure 5, PLC-system with feedback and AD/DA-modules

The AD/DA-modules can further be broken down in to channels, where one channel handles one specific signal. A typical module consists of four channels. The input channels on an AD-module are used to sample and convert incoming values. The two most common practises being average processing and continuous sampling processing [5]. The former continuously calculates an average value for incoming values where the number of measured values can be set to either a time- or an amount constraint. The latter method converts incoming values one by one; this method could be preferred when delays in the data-handling are unwanted. However, by using an average sampling process, the converted value could be made less susceptible to noise or other unwanted anomalies or disturbances. The resolution of the AD/DA modules are determined by a combination of the bit size available for the respective channel and usually an internal setting of the module which is slightly lower than the available bit-range [5].

Other important hardware aspects of PLC-module are: internal memory, which needs to be adapted to the intended use, removable memory, for accessing saved data, often an SD-slot, communication interfaces, between external computer and PLC for downloading and uploading data, as well between the PLC and the HMI. An example of a typical HMI could be customizable touchscreens with ethernet communication between it and the PLC from which an operator could control the PLCs´ functions.

A PLC has a cyclic mode of operation. These operations are three steps and can be described as [2]:

1. Read. The PLC reads the status off of the utilized inputs. For example: if the input is high, a 1 is written to the inputs corresponding memory address and vice versa.
2. Run. The PLC runs the current active user-created program. This program might alter values of variables designated as outputs based on it´s logic structure and together with input values. Therefore, if an output is programmed to be altered, a corresponding value is written to the outputs memory address.
3. Write. The outputs are activated, turned off or assigned a specific value corresponding with their respective memory cell.

The mode of operation needs to be accounted for when programming a PLC, for the PLC to function as intended [2], which will be further explained in section 3.2.3.

3.2.3 Programming Languages

The logic rules/operators used in a PLC-program editor can be represented in a number of different ways. For instance, a typical PLC is capable of utilizing a combination of text-based code together with symbols and other types of visual objects which together can form logic[7]. Figure 4 is an example of one programming language Ladder Diagram, LD. Here, the left-hand side represents +24 volts and the right-hand side represent 0 volts. When a row is connected, from left to right via push-buttons, X1, or other inputs, current can flow, and the outputs, Y1, are altered. The shape of the sides and rows are similar to that of a ladder, hence the name.

By adding text-blocks on a row you can implement text base code in the Ladder Diagram. The code that is written in the text blocks are referred to as Structured Text, ST, and is a separate language [3]. Syntax differs between manufacturers but the combination of the two ways of programming is often available [3].

Another way of combining the Ladder Diagram language, is with Function Block Diagram(FBD). These are functions to convert Ladder Diagram logic into a single component [3]. If one function is used repetitively in a program, this could be an effective and less error-prone method of writing that function and calling the function when need be. FBDs are visualized as blocks with inputs and outputs with their own set of internal logic [3].

Other useful languages are: Instruction List(IL) where commands are written in a list and executed in that same order [2], and Sequential Function Chart(SFC), which is a high-level chart consisting of steps of every unit of operation [6]. The operations are in turn a combination of previously mentioned languages controlling machine operation.

3.2.4 Editors

A typical Mitsubishi PLC contains RUN, RESET and OFF-mode, making it mandatory for the PLC to use external programs to function [8]. These might include: code editors, HMI editors and simulation programs.

PLC manufacturer often utilizes their own editor programs. Mitsubishi PLCs, utilizes the editor GX Works(Figure 24). As the subject for this thesis is a machine which uses a Mitsubishi PLC. GX Works will therefore be used in this thesis and is an editor that handles all of the previously mentioned languages, i.e., LD, ST, IL, SFC and FBD. GX Works and other similar programs is run and compiled on separate computers and the code is downloaded to the PLC via a physical connection [3].

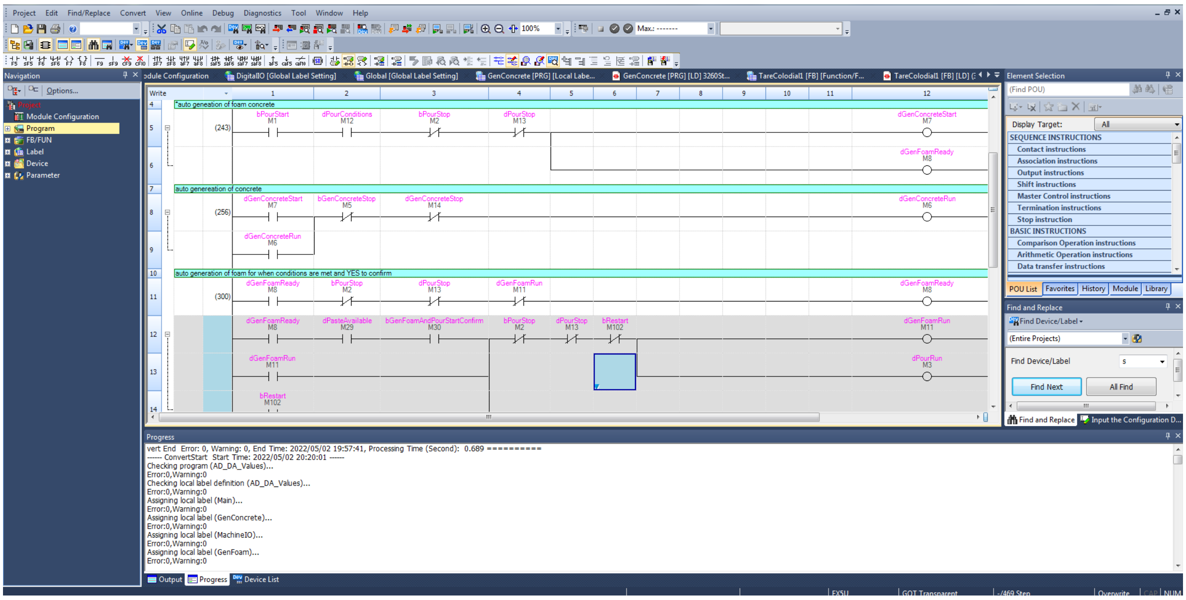


Figure 24, GX Works 3, general layout.

Additional external programs are required for when implementing HMIs. Mitsubishi GT Designer(Figure 25) is used for Mitsubishis HMI touchscreens and is highly customizable. GT Designer enable functions for live information display, such as temperatures or flows from different sensors. In addition, the HMI-editor allows for control of the PLC-program by using digital buttons and menu systems. In terms of interface, GT Designer 3 is in general a drag-and-drop based program. Buttons, displays, graphs and dialogue functions can be configured so that they are connected to specific variables on the PLC and can showcase the same information in GT Designer while editing, for example variable name and register [4].

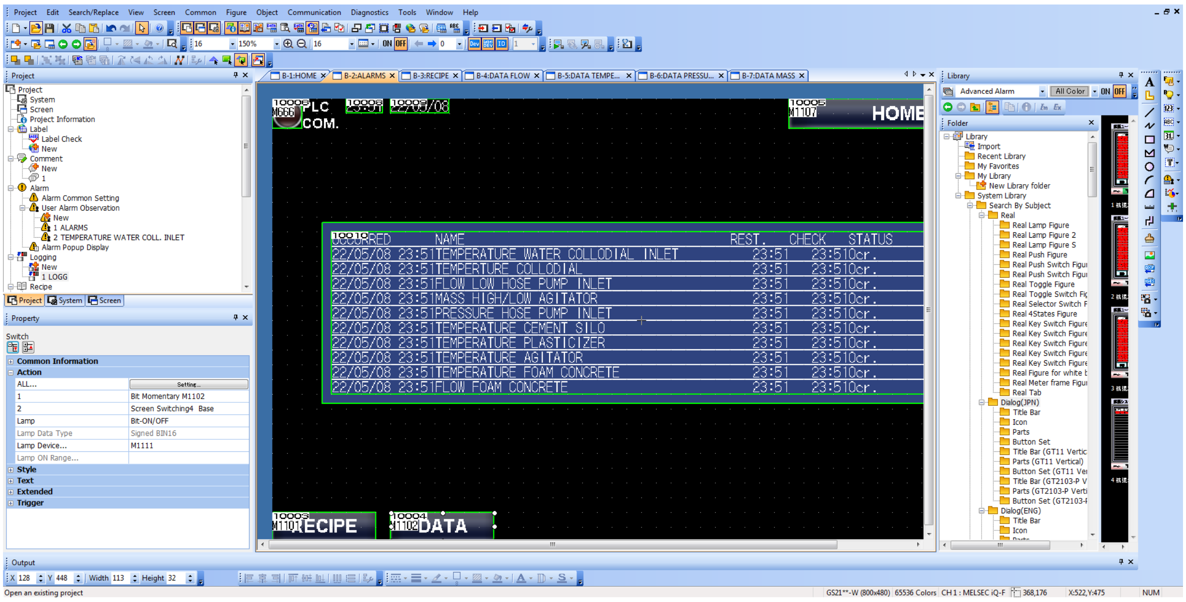


Figure 25, GT Designer 3, general layout.

4 Method

This chapter will include a brief technical description of the prototype and the specified capabilities and criteria of the LS-machine based on the assignment from the company, as well as the thesis work method.

4.1 Prototype description

4.1.1 Hardware and interface

The prototype can be divided in to three sides: A-side and B-side, which joins together to form C-side. A-side and B-side create the separate fluids A and B, using compounds a1, a2, a3, b1, b2, b3 respectively. Fluid A and fluid B are then used as compounds to create fluid C, i.e., the product. Figure 26, below, displays a basic scheme of the prototype.

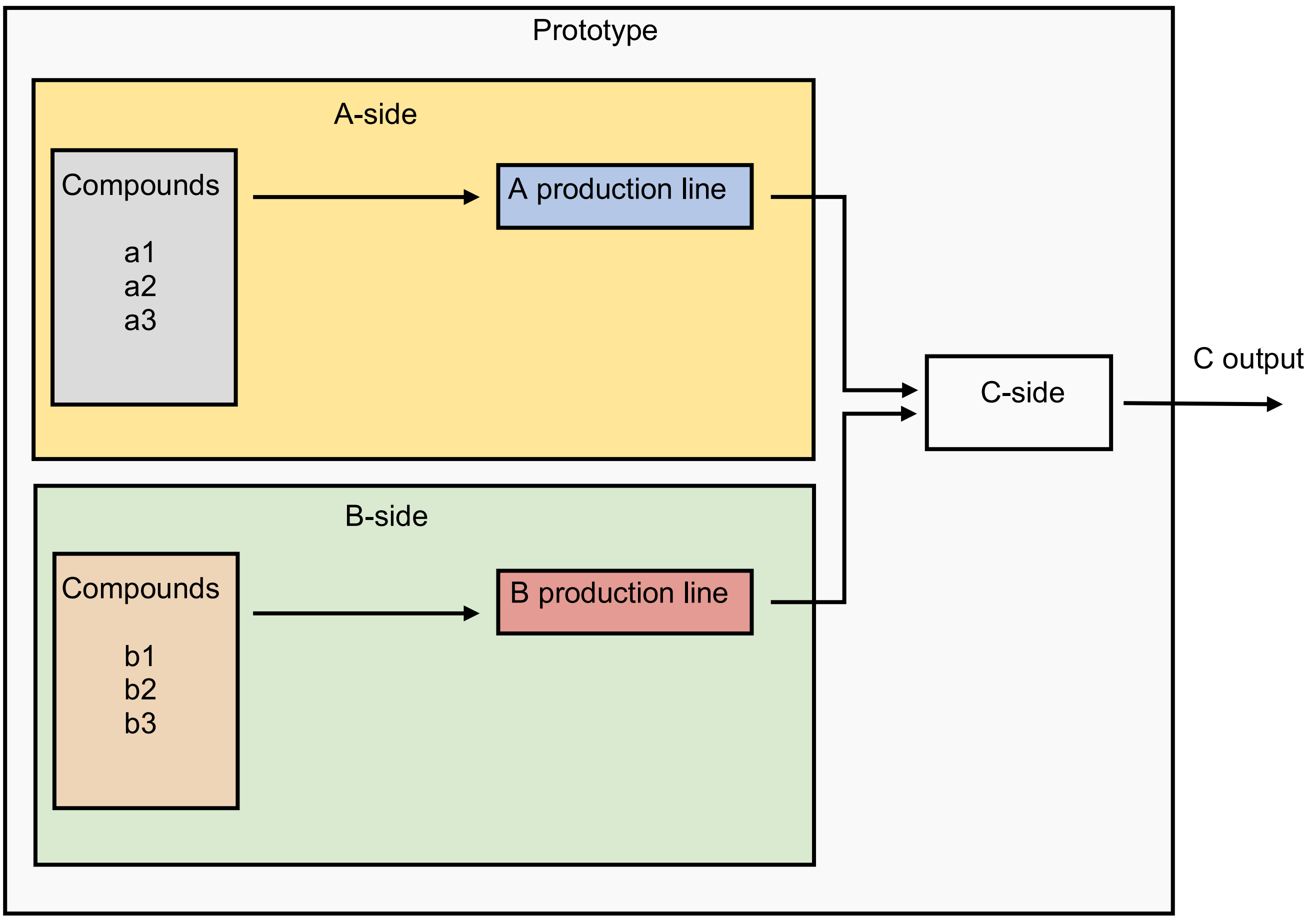


Figure 26, prototype overview

The prototype operates on 400 V 32 A electrical power and also uses 12 and 24 V for PLC and machine control. The prototype is run from a central position using a Mitsubishi GOT 2000-series Touchscreen connected via ethernet to a Mitsubishi FX5U PLC. The HMI contains menus and settings for machine operation, separate manual operation of components as well as an automated mode which is used for producing fluid C.

On the A-side of the machine there are physically larger three-phase machines, such as a mechanical conveyor, agitator, colloidal mixer, vibrators and a high-capacity peristaltic hose pump. On the B-side there is a small one-phase precision pump, a larger three-phase pump, inlets and valves. Finally, on the C-side there is a blender, which mixes A and B. On both the A and B-side there are pneumatic valves and cylinders used for opening process hoses and directing flow.

Furthermore, the prototype utilizes multiple types of sensors. On the A-side there are three load cells on the colloidal mixer, a speed and direction sensor on the hose pump, and after the hose pump, a flow meter and a pressure sensor. On the B-side there are PID-controllers and flowmeters controlling the mixing of compound b1 and b2, a separate flow meter in the precision pump controlling compound b3 and pressure sensors.

All of the PLC´s logical outputs use 0 and 24 volts, where 24 being high, and all of the sensors I/O use 4 – 20mA where 4 being 0.

The prototype contains two AD/DA expansion modules creating a total of eight AD inputs and eight DA outputs. These modules have a resolution of 14 bits, 16383, but an internal numerical limitation of 12 800 on the input. 20 mA would then represent 12800. On the output, for example instructing the hose pump to run at maximum RPM, the maximum is however 16 000. All of the sensors except the load cells utilize average sampling.

For converting values from input on the HMI to the PLC and displaying actual physical values on the HMI, a scaling factor is used. The communication between the HMI and the PLC only allows integer values so the following formula is applied:

$$Scaling\ factor = 10^n \quad \text{(i)}$$

where n is the number of decimals on the input value. For example, the value of 2,55 as numerical input would then be scaled to 255, as it contains 2 decimal points. Another scaling is done when reading data from sensors. The following formula is applied:

$$Scaling\ factor = \frac{M_P}{M_D} \quad \text{(ii)}$$

Where $M_P$is the maximum physical value from the sensor and M_D is the maximum digital raw value, in our case, 12 800. In the prototype PLC, only the raw values are handled because of a small number of AD inputs. The small number make each value unique and differentiable, making physical value-conversion and labelling unnecessary.

4.1.2 Prototype software

The prototype software is compiled using Mitsubishi GX Works 3 with a combination of LD and ST. The HMI software is compiled using GT Designer 3. The internal registers of the PLC that are being utilized are M and D, where M is used for logical variables, and D can be used for logical as well as numerical values. As previously mentioned, the software can be divided in two general modes of operation, manual and automatic. Where manual gives the operator the ability to run each component separately. The automatic mode is used for running the A-, B- or C-side either in parallel or the A-side first and then B- and C-side in parallel.

4.2 Description of LS-machine

The LS-machine will be based on the prototype in terms of functions, mode of operation and compound handling.

The most substantial change from the prototype compared to the LS-machine is the larger scale, i.e., a higher output capacity. In addition to the changes to the LS-machines dimensions, the LS machine will also handle compounds differently throughout its respective process lines. The output will also have to be continuous, as on the prototype, which also adds to the strain of the process chain. The initial rough estimate is that the LS-machine will have an output capacity ten times that of the prototype. For the sake of the thesis, the exact value is not irrelevant. However, it is highly relevant to implement functions and machinery with a high degree of output flexibility.

Compared to the prototype, the LS-machine will incorporate quality control functions. These will include data logging of processes and further monitoring of the production process through additional sensors. Another quality control measure is interrupt routines along with alarms. These should be highly customizable to suit their respective needs and serve as indicators for the operators when anomalies arise. The alarms can be used to turn off machine components automatically if an anomaly is detected. Another reason implementing alarms is to elevate the operating safety, especially when handling high pressure processes.

Additionally, the LS-machine will incorporate some form of recipe handling and improved HMI graphics. These are functions that greatly simplifies the operation of the machine by reducing the required steps to produce C and making the process easier to observe and evaluate, therefore also decreasing the work load for the operator. An example of HMI graphics might be live graphs indicating storage levels of the process compounds.

4.3 Thesis method

This section will include the different methods used achieving the requirements outlined for the LS-machine control system.

4.3.1 Control system requirements

The functions of the LS-machine, and implementing those functions, was at the heart of the thesis project. This meant that a dialogue with concerned parties at the company, along with working through documentation, as well as operating the prototype served as pivotal steps in understanding the requirements for the LS-machine. The requirements of the LS-machine control system were summarized as:

- (1) Control of higher output capacity compared to the prototype, 10:1.
- (2) Implementation of quality control functions.
- (3) Improved and implemented HMI functions.

4.3.2 Compiling software

The control system-software for the LS-machine were based on the control system-software of the prototype machine. The first step of the process was to early identify parts of the prototype control system that could be carried over to the LS-machine. During this initial step, it was determined that the B-side of the production process was highly specialized and key to the production process.

The B-side contains certain information regarding handling of the b1, b2 and b3 compounds in a certain specific way to generate a specified output of B and, in turn, C. The B-side will not, therefore, be presented in the thesis report. By using the critical functions of the B-side from the prototype in the LS-machine, the risk is minimized that there is a loss of function regarding production of B from a software standpoint. Another reason to base the LS-control system on the prototype system is that the machine in general is a proven concept regarding handling of material. To summarize, the main parts that were transferred to the LS-machine control system from the prototype control system was:

- Production-control of B, with certain change to flow capacities to facilitate the larger total output rate.
- A-side infrastructure, with major changes regarding capacity to handle larger total output rate.
- Interface structure, with major changes regarding I/O capacity.

For implementing (1), *Control of higher output capacity compared to the prototype, 10:1*, the A-side of the LS-machine was duplicated in to three parallel production lines; designated A1, A2 and A3. This increases the total output of A by three times. By further increasing capacities of components along the production line, the capacity could reach a factor ten. For example, increasing the first stage mixers were a1, a2 and a3 are mixed, by a factor of 1.5 would generate a batch-output of $900l/5min$, 5 minutes per batch. This output would in turn balance the output from the storage tank of A, since that requires an output of $180l/min$. While the hardware-related questions are outside of the scope of this thesis, the control system should allow for a certain flow, which in turn has a direct effect on hardware design. Therefore, certain recommendations are provided in section 6.2. The duplication of production lines meant designing a control system that would allow for three parallel production lines that work individually or together, depending on process status, adjusting to produce the correct mixture of C.

Implementation of (2), *Implementation of quality control functions*, was achieved by adding sensors along the A-, B- and C-side of the production, to surveil and verify the process. The sensors include additional load cells for added containers, to measure compound mass along the process, additional flow sensors, to measure momentary flow in various machine components, and adding of temperature and pressure sensors, to measure temperatures in containers and storages, and pressures of compounds. These were monitored with separate alarm-functions corresponding to their intended use. This not only enables enhanced monitoring of separate flows, but could also increase safety during operation by monitoring high pressures and flows. The additional data these sensors provide were, in addition to providing the operator with real time data, logged in a database, providing traceability for future quality evaluations.

Implementation of (3), *Improved and implemented HMI functions*, a simplification of the HMI in order to reduce work load for the operator, possibly reducing risk of operator related errors. To achieve this, software development focused on increasing the level of automation for the respective product lines reducing steps needed to produce C. To further clarify machine operation for the operator, visual aids were made available through the built-in functions of GT Designer such as live graphs displaying relevant operational information. In addition, a recipe handling system were implemented with the purpose of increasing operational efficiency.

Throughout the thesis, Mitsubishis extensive manuals have been used as references for practical guidance. The manuals include: GX Works 3 Operating Manual, GT Designer Version1 Screen Design Manual, GX Developer Version 8 Operating Manual, MELSEC-Q/L/QnA Programming Manual, GOT2000 Series User´s Manual along with the respective programs built-in help sections.

4.4 Source Criticism

The sources used in the thesis are almost all exclusively derived from Mitsubishi Electric Corporation which makes them relevant to use for the thesis because of the pre-selected hardware (Mitsubishi). Furthermore, due to that almost all of the sources are instructions or manuals they are objective and therefore have no reason to be questioned with regards to its content.

5 Result

This chapter describes the results of the implemented, outlined control system requirements, which are: (1) *Control of higher output capacity compared to the prototype*, *10:1*, (2) *Implementation of quality control functions*, (3) *Improved and implemented HMI functions*. AD/DA-values handling will also be presented in this section.

5.1 Increase total output.

To enable an increase in total output by 10:1, the control system for the production line of A was redesigned with three parallel production lines on the A side, A1, A2, A3. The control system allows for the three lines to run simultaneously, increasing the output of the A-side by a factor of three, and together with hardware improvements, could reach a factor of 10. Figure 27, below, displays a basic scheme of the LS-machine based on the thesis results.

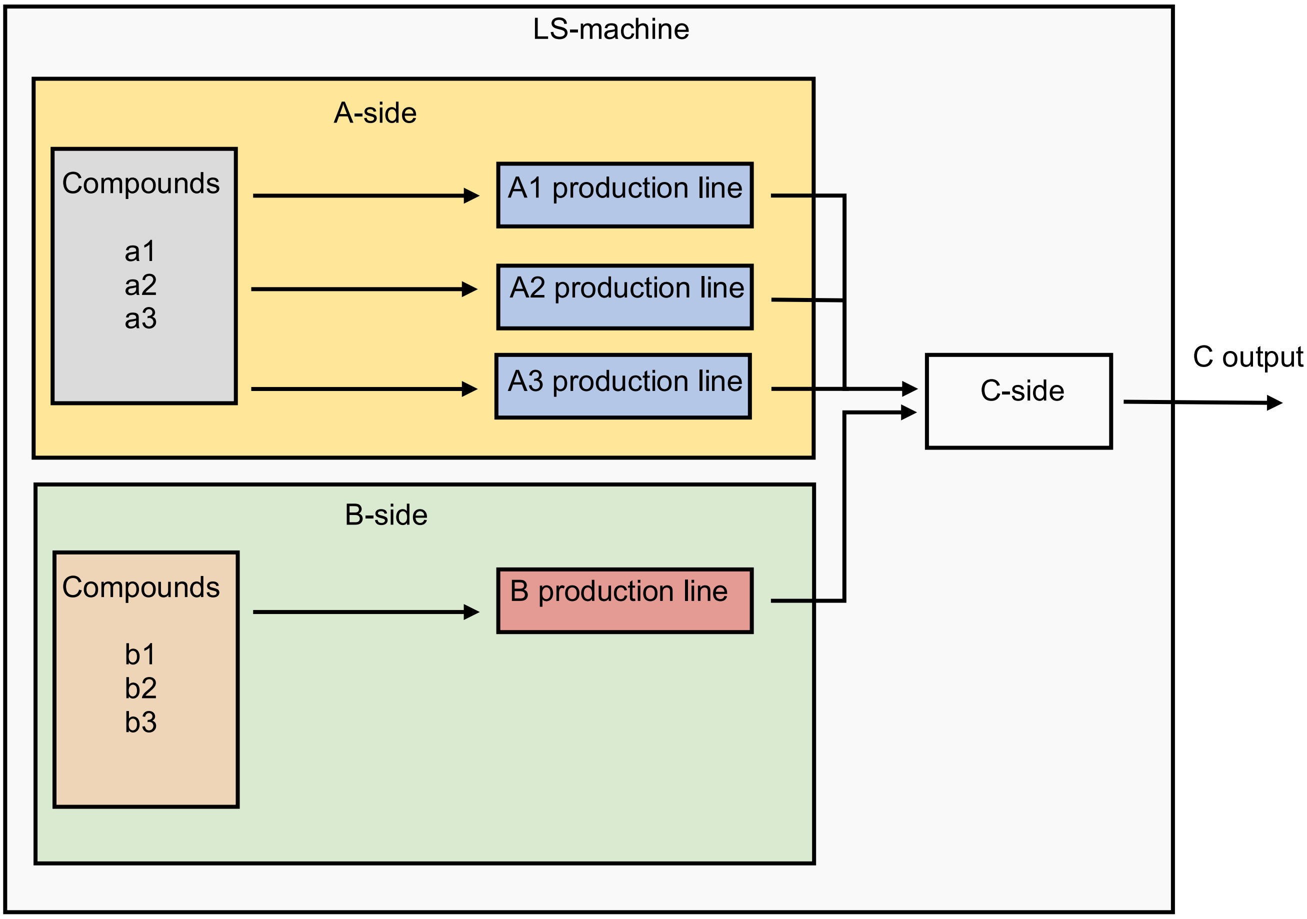


Figure 27, LS-machine overview based on thesis results

The A-side control system utilizes a state-based ladder system in which the program enters and exits different states depending on local conditions. As an example; if the program has reached the final state for generating a batch, a condition is then run and based on the outcome of the condition, the program enters another state.

When allowing for A1, A2 and A3 to run simultaneously, and since the A-side process produces batches with an integer-quantity, eventually a process-situation will arise when it´s not necessary to run all of A1, A2, and A3 at the same time. Basically, when there´s only need for one or two additional batches. A function was therefore implemented which determines if the total batch number is approaching the batch goal. The function works as follows and in this order:

- Increment the current value for batches made.
- Compare the current value to the batch number goal.
- If they are equal, set certain state for only running A1.
- If they are not, the current value is again incremented.
- Comparison operation is run again.
- If they are equal, set certain state for only running A1 and A2.
- If they are not, set certain state for running A1, A2 and A3 together.
- Current batch number reduced to its original value after function usage.

This function is run after every time the production process utilizes A1, A2 and A3 together. As an example; if the batch goal is set to four, then A1, A2 and A3 are run once, and then A1 once.

To further increase control of the separate flows, pumps and pneumatic valves was added. These are all controlled automatically based on which state the program sequence is currently at.

Furthermore, another implemented function was the ability to input the total desired output of C from the LS-machine. This has not been an option for the prototype, since it usually handles smaller quantities of C compared to the LS-machine. The function is necessary when handling larger quantities with the LS-machine, in order to reduce operational errors. The number of batches to be produced on the A-side are calculated based on the desired total output of C. The actual total output of C is also measured, utilizing a flow meter and integrating the flow-reading over time, presented in section 8.5.

The A-side program has, as described in previous sections, been simplified in regards to operator work load compared to the prototype by decreasing the number of available process settings. This in turn can possibly reduce the risk of operator generated errors.

The program for production of A is roughly 330 LD-rows long and will therefore not be presented in its entirety in the thesis. However, selected parts are provided in section 9.2.

5.2 Quality control

Improvement of the quality control in the control system design was implemented by creating functions for the sensors and the logging function. To provide sufficient sensor coverage and alarm functions, sensors were added mainly on the A-side of the production but also to the B- and C-side. Section 9.3 provides example illustrations of the logging function and alarm function.

The added sensors consist of:

- Five flow meters placed on strategic locations. The locations were based partially on previously unmonitored areas, as well as areas that are under sustained high pressures with regards to flows. The flow meters all use average sampling conversion. Process-critical flow meters have alarms that are turned on when fluid passes through them, enabling them to activate if a flow is detected outside it´s excepted range. The range for the alarm is set in GX Works. For example, the flow meters on the A-side have an alarm-range for detecting the absence of flow by using a low-limit for the alarm range that is below the normal value for that specific process point. By further utilizing a delay-function for when the alarm itself can function, the alarm isn´t activated prematurely.
- 15 temperature sensors in total were added to the production lines. They are especially important to utilize on the compound inputs, making sure that they are within their respective allowed temperature ranges. As with the flowmeters, average sampling is used. There are no alarm functions coupled to the temperature sensors, because of a, probable, manageable rate-of-change in temperatures, but each sensor has a true-value output in the HMI, creating an overview of the current temperatures.
- Furthermore, eight pressure sensors were added for detecting abnormal pressures and therefore reducing production errors as well as increasing operational safety. The pressure sensors were added on high pressure

areas on the A-side and C-side of the production. These sensors have alarms and work with a high range-limit for the alarm range. As with the flow sensors, the alarms can only be active when there are supposed to be fluids present around the sensor.

- Additionally, six load sensors were added on the A- and B- side on containers and silos, further securing the process lines by making the material-stocks more easily to overview. As with the previous sensors, the load cells also use average sampling. No alarms are currently connected to the load cells, but if needed, is implemented as other alarms. The output of the loadcells were made visually represented in the HMI.

The above-mentioned pressure and flow sensors each have alarms connected to their functions. The alarms are handled with the built-in alarm function of the GOT2000-series. The function provides an interface on the touchscreen where alarms can be stored, reset or checked. The characteristics of the alarms are all individual and has been implemented in GX Works.

The built-in logging function of GT Designer and GOT2000 was utilized and 17 different parameters can be logged for 60 minutes, initialized when the process starts, and sampled every second for each parameter. The number of sampled values can be changed, as well as run-time and interval. The values are written to a text file and automatically saved in to the PLCs SD memory card. The logging parameters include: local weather data, such as air humidity and air temperature, along with process settings and parameters. The text file can then be analysed in a PC allowing for flexibility in future analysis methods. The logging ends when production of C ends.

5.3 Improved HMI

The control system has been simplified by reducing the amount of required operator inputs by emphasizing automated processes. As previously stated, this reduces the risk of operator generated errors. The production process of C can be started, paused, restarted and stopped from the home screen on the touchscreen. Section 9.4 provides example illustrations of the touchscreen-based HMI. The home screen presents the most relevant process data; visual representation of storage levels, temperatures, weather information, flows and output volumes. Additional screens display alarm interface, recipe input and process data, the home screen can be accessed directly from every separate screen. Every screen also has access to every other screen along with an alarm light that indicates when an alarm is active.

The recipe handling function were built using the standard GOT2000 series function, much like the alarm and data-logging. This standard function of the GOT2000 was utilized and configured to handle the inputs to recipes as well as to save and load recipes to and from the SD-card, allowing for documentation or modification on a PC. The interface is that of input displays and the built-in recipe handler are accessed through the GOT2000s´ internal utility system. Overall, the LS-machines HMI has a simpler menu system, featuring fewer sub-menus, compared to the prototype HMI, as well as fewer input options, more accessible data and more functions. The added functions, such as the alarm-system, allows for a higher degree of quality assurance throughout the machine operation. Section 9.3 provides example illustrations of the recipe function.

5.4 AD-values

In this chapter, the handling of AD-values for the control system for the LS-machine will be further explained, given that AD-value processing is a substantial part of the control systems operation. Section 9.4 provides example illustrations of the handling of AD-values.

The AD-modules were modelled with a resolution of 14 bits, without internal limitation. The internal resolution limitation is not relevant to the thesis and is easily adjusted for when future hardware is specified and applied. The additional sensor inputs and other added inputs combine to a total of 42. This means that the LS-machine will need at least 42 AD-inputs to the PLC. If the AD-module configuration is the same as on the prototype, an additional nine AD-modules are needed, which in that case would facilitate four inputs/channels each. The adding of AD-modules would be the single largest physical change regarding the control system, and its corresponding electrical cabinet layout, a factor to take in to consideration when designing the LS-machine.

Conversion from AD-input values in to physical values were done in the PLC, through GX Works, for the LS-machine, unlike the prototype, because of the more user-friendly implementation methods of GX Works. The values are then scaled for the communication between PLC and GOT2000. The conversion to physical values is based on the two factors, M_P and M_D from formula (ii). Using physical values, instead of raw values, in GX Works proved effective when later implementing them in GT Designer for operator use, as well as determining alarm ranges, due to that the high number of inputs could be processed in groups, which is not possible, in GT Designer.

Each AD-input corresponds to a channel on AD-modules [9]. The channels are in general assigned a certain name, relating to their function. For example, on the prototype, an AD-input is assigned SD6300, which corresponds to "Channel 1, analog input value" [9]. These labels are dependent on the type of AD-module that is eventually specified for the LS-machine, and are, similar to setting the internal AD-resolution limitations, determined by reviewing relevant instruction manuals for the specified hardware [9].

The preferred, and utilized, sampling process was average sampling throughout the LS-machine sensor-spectrum, to achieve the highest possible accuracy throughout the process. The prototype uses this sampling type on most of its inputs, the load cells use continuous sampling to avoid a measuring delay. However, for the LS-machine, the benefit of using the more accurate average sampling outweighs the disadvantages of the marginal delay.

6 Discussion

6.1 Control system operational requirements

The control system operational requirements are 230V AC for PLC power, 24V DC for HMI power along with 12 and 24V DC for sensor control and power. Three phase machine components require 400V AC. A larger electrical cabinet for facilitating the control system is needed along with redesigning of infrastructure regarding the vast number of sensors. Further operational requirements can be specified when hardware components have been specified.

6.2 Hardware suggestions

A list of hardware suggestions will follow that can be used with regards to how their respective functions are implemented in the control system, such as alarm functions, control and so on. The list includes significant, selected thesis-relevant components. In chapter 8, section 1, the respective datasheets are presented. A complete component suggestion can be further specified in dialogue with the company.

- Hose Pump:
  Bredel 65. A peristaltic hose pump from manufacturer Bredel. Low maintenance due to pump design; The pumped material never contacts vital pump components. Maximum capacity of 32 000l/h for intermittent duty and 20 000l/h of continuous duty. The LS-machine will have a continuous flow of ca 11 000 l/h. Alarm function in LS-machine-control system are designed with the maximum outlet pressure for the Bredel 65 of 16 bar. LS-machine control system-compatible input of 4-20mA.
- Pressure sensors:
  WIKA S-11. A pressure sensor from manufacturer WIKA with built-in transmitter. For general industrial application. Maximum pressure measuring range is flexible and within the LS-machine requirements. LS-machine control system-compatible output of 4-20mA.
- Flow meters:
  KROHNE Optiflux 4000. An electromagnetic flow sensor from manufacturer KROHNE. Suitable for industrial use and for slurries with high solid content. Installed together with compatible KROHNE IFC 300 signal-converter. LS-machine control system-compatible output of 4-20mA.

- Temperature sensor:
  WIKA TFT35. A temperature sensor from manufacturer WIKA with built-in transmitter. For general industrial application. Vibration-, and high-pressure resistant. LS-machine control system-compatible output of 4-20mA.
- Compound b1 pump:
  IWAKI IXD 300 TC/TE. A high precision dosing pump from manufacturer IWAKI. Suitable for high accuracy demand pumping and industrial use. Min/max flow of 0.4-300l/h. LS-machine control system-compatible input and output of 4-20mA.
- Load cell:
  Eilersen BM-Ex. A beam load cell series from manufacturer Eilersen. Suitable for industrial use. Hermetically sealed. Wide range of maximum capacities, all with LS-machine control system-compatible output of 4-20mA
- PLC
  Mitsubishi FX5U-80MT/ESS. High-capacity PLC from manufacturer Mitsubishi. 40 digital inputs, 40 digital outputs. Within the I/O requirements for the LS-machine. Expandable, ethernet port for communication with GOT2000-series HMI.
- HMI:
  Mitsubishi GT25, included in the GOT2000-series. HMI from manufacturer Mitsubishi. Robust design, suitable for harsh industrial use. Touchscreen, TFT, ethernet communication to PLC and SD memory card slot.
- AD-module:
  Mitsubishi R60AD16-G from manufacturer Mitsubishi. A high-capacity AD-module with 16 analog input channels, 4-20mA. Choosing the same brand as current control system can make future implementation simplified.

6.3 Simulation

Understanding the scope of the thesis has been a substantial part of the work process. What follows is a summary of the different areas of discussion leading up the thesis scope.

The scope was altered slightly along the line of the thesis: initially, much time and effort were spent on investigating if and how simulating the control system for the LS-machine would be a viable part of the thesis, for the sake of verifying the function of the produced software. The outcome of this was that it was not viable, as follows.

Initially, construction of a physical model of the LS-machine was discussed. A model with flows of roughly a 1:100 scale of that to the LS-machine, to serve as a software testbench. This option was mainly deemed too time consuming, along with eventual problems occurring with different behavior of flows of the respective compounds. Furthermore, machine parts along with their respective interfaces might not have functioned properly with limited flows, given that not too many compromises were taken in choosing hardware. For example, dosing of certain compounds that are not fluids would need intricate handling systems in order to make the dosing exact, possibly changing the software structure, this specific reason was not however investigated thoroughly. Another aspect of constructing a physical model was the question of cost along with necessity of the model after the finalization of the thesis.

A second option for verifying the software was to model the LS-machine in a simulation environment, such as Matlab. This option was also deemed too time consuming to fit within the scope of this thesis due to the complexity of such a model.

A third option for verifying the software was to use GX Works 3 and GT Designer 3s combined sub-program called GT Developer 3. This program functions as a virtual link between the HMI and the PLC and serves as an interface in which the PLC-code can be “run” from. The PLC-code receives input from, and can send outputs to, the HMI via GT Developer and the entire system works as a simulator. However, GT Developer only works with input from the HMI making it not useful for the thesis application as external inputs are required for the control system to function, for example sensor inputs. Sensors and their respective interfaces on the LS-machine would need to be modeled, as there is no realistic way of manually setting each value. One way of solving this issue could have been to create variables with non-static values that would represent the measured value along with programming some behavior within GX Works. This behavior would have to be simplified and not an exact physical representation, limiting its usefulness for verification, as there are almost 50 different inputs to the PLC.

6.4 General

Regarding the production of A. It might be viable to change all of the mass-based, high precision conditions to flow-based. Considering that the LS-machine will be mobile, albeit not while it´s operational, and therefore depending on how it´s positioned when operational, the load cells might be affected. This might happen due to positioning of the LS-machine in relation to wind direction and if it´s positioned in an incline.

Regarding the handling of C. This question lies in the grey area of what´s included in the scope of the thesis; adding of hardware after the output of C to increase C´s ability to be physically moved over greater distances. This might include an additional buffer-storage and pump with relevant sensors and required control. If so, it can easily be added and implemented. There are no limitations in the control system if this feature is wanted. Overall, the suggested PLC currently has 8 remaining available analog outputs that can be used for machine components.

Regarding HMI. Considering the large quantity of available sensor data with endless configuration possibilities, user-based testing should be the final decider of the design of the GOT2000-series touchscreen. The GOT2000 can be tested and redesigned in very short notice, if need be, in GT Designer. Another aspect of the HMI is to expand it, utilizing additional GOT2000-series touchscreens, preferably where one serves as the master screen, and others used as monitoring data. The data-screens, for minimising risk of operator related mistakes, should have no possibility to run or control the machine process apart from stopping it, with regards to safety. Additionally, physical emergency stops should be implemented on the machine wherever there is risk of mechanical or other types of dangers, but this is also a hardware related question as they are most likely hard-wired to the power of the entire machine.

The framework for the control system for the LS-machine can be considered completed. It is not an entirely applicable system and will need modification to comply with future specific interfaces and hardware/software component choices. The framework is however highly flexible for utilization of industry standard interfaces, such as 4-20mA sensor-output current.

A report intended specifically for the company containing more specific, information and lessons learned will be produced and handed over in May-22.

6.5 Ethical aspects

The thesis involves utilizing instructions and manuals provided mainly by Mitsubishi Electric corporation. The thesis work is therefore an interpretation of mainly Mitsubishis´ already established knowledge regarding PLC design and structure. Because of this, the thesis work can therefore be viewed as expanding and broadening the use of Mitsubishi PLC-structure and design.

The purpose of the thesis work is not contributing to decreasing work opportunities for humans due to that the LS-machine, and its control system, is not replacing any current or planned work opportunities. One could argue that the purpose of the thesis work does the exact opposite because that it already lays one part of the LS-machine-puzzle, which in the completion process will demand PLC- and machine-engineers, computer aided-design engineers, procurement-functions and other functions and specialists.

From an environmental standpoint, the thesis work in itself has had a limited effect to our environment because all of the work has been done on a standard PC and, for most of the time, from one geographical location. The purpose of the LS-machine and the thesis involvement in that with regards to our environment is more substantial, compared to the actual thesis work.

7 Terminology

I/O	Input/Output
PLC	Programmable Logic Computer
AD/DA	Analog to Digital/Digital to Analog
Off-the-shelf	Standardised, commonly used products or components
mA	Milli-Ampere
V	Volt
HMI	Human-Machine-Interface
LD	Ladder Diagram
FBD	Function Block Diagram
IL	Instruction List
SFC	Sequential Function Chart
A/B/C-side	Different separate machine production lines

8 References

[1]. Electronics CSM, *Grund och fortsättningskurs Q-serien,* Beijer Electronics, *2008.*

[2]. Mitsubishi Electric Corporation, *PLC Programming Basics,* [online document], 2015, Available: https://www.mitsubishielectric.com/fa/assist/e-learning/pdf/eng/1-Program_Basics_na_eng.pdf [Accessed: May 21, 2022].

[3]. Mitsubishi Electric Corporation, *GX Works3 OperatingManual*, [online document], 2015, Available: https://dl.mitsubishielectric.com/dl/fa/document/manual/plc/sh081215eng/sh081215engag.pdf [Accessed: May 21, 2022].

[4]. Mitsubishi Electric Corporation, *GT Designer3 Version 1 Screen Design Manual (Functions) 1/2,2/*, [online document], 2020, Available: https://dl.mitsubishielectric.com/dl/fa/document/manual/got/sh080867eng/sh080867engai.pdf [Accessed: May 21, 2022].

[5]. Mitsubishi Electric Corporation, *Analog-Digital Converter Module User´s Manual*, [online document], 2021, Available: https://dl.mitsubishielectric.com/dl/fa/document/manual/plc/sh080055/sh080055t.pdf [Accessed: May 21, 2022].

[6]. Mitsubishi Electric Corporation, *MELSEC-Q/L/QnA Programming Manual*, [online document], 2009, Available: https://dl.mitsubishielectric.com/dl/fa/document/manual/plc/sh080041/sh080041x.pdf [Accessed: May 21, 2022].

[7]. Mitsubishi Electric Corporation, *GX Developer Version 8 Operating Manual*, [online document], 2010, Available: https://dl.mitsubishielectric.com/dl/fa/document/manual/plc/sh080373e/sh080373ean.pdf [Accessed: May 21, 2022].

[8]. Mitsubishi Electric Corporation, *Mitsubishi Programmable Controller Training Manual Q-series Basic Course*, [online document], 2012, Available: https://dl.mitsubishielectric.com/dl/fa/document/manual/school_text/sh081123eng/sh081123enga.pdf [Accessed: May 21, 2022].

[9]. Mitsubishi Electric Corporation, *MELSEC iQ-F Series iQ Platform Compatible PLC*, [online document], 2020, Available: https://dl.mitsubishielectric.com/dl/fa/document/catalog/plcf/l08428eng/l08428eng-f.pdf [Accessed: May 21, 2022].

9 Appendix

The entirety of the LS-machines control system is not presented in the appendix.

9.1 Datasheets, suggested hard-ware components

Hose Pump: https://www.wmftg.com/v1.0/Documents/knowledge-hub/Datasheets/gb%20-%20UK/Bredel%20rebrand/wd-bredel_65_80_100-en-06.pdf

Pressure sensor: https://www.wika.com/media/Data-sheets/Pressure/Pressure-sensors/ds_pe8102_en_co.pdf

Flow meter: https://www.fagerberg.se/wp-content/uploads/2022/02/TD_OPTIFLUX4000_en.pdf

Signal converter: https://www.fagerberg.se/wp-content/uploads/2022/02/TD_IFC300_en.pdf

Temperature sensor: https://www.wika.com/media/Data-sheets/Temperature/Resistance-thermometers/ds_te6718_en_co.pdf

Compound b1 pump: https://iwaki-nordic.com/literature/dosing_pumps/direct_drive/ix-d/brochure/IX-D_brochure_uk.pdf

Load cells:
https://eilersen.com/fileadmin/user_upload/Print_Data_Sheet/2022/BM_70__BM-Ex_70__Data_sheet.pdf

PLC: https://se.mitsubishielectric.com/fa/products/cnt/plc/plcf/cpu-module/fx5u-80mt-ess.html#tab-bltfbdbcff971f9343a

HMI:https://se.mitsubishielectric.com/fa/products/hmi/got/got2000/gt25rugged/gt2507t-wtsd.html#tab-bltfbdbcff971f9343a

AD-module:
https://www.mitsubishielectric.com/fa/products/cnt/plcr/pmerit/analog/input.html

9.2 (1) Control of higher output capacity

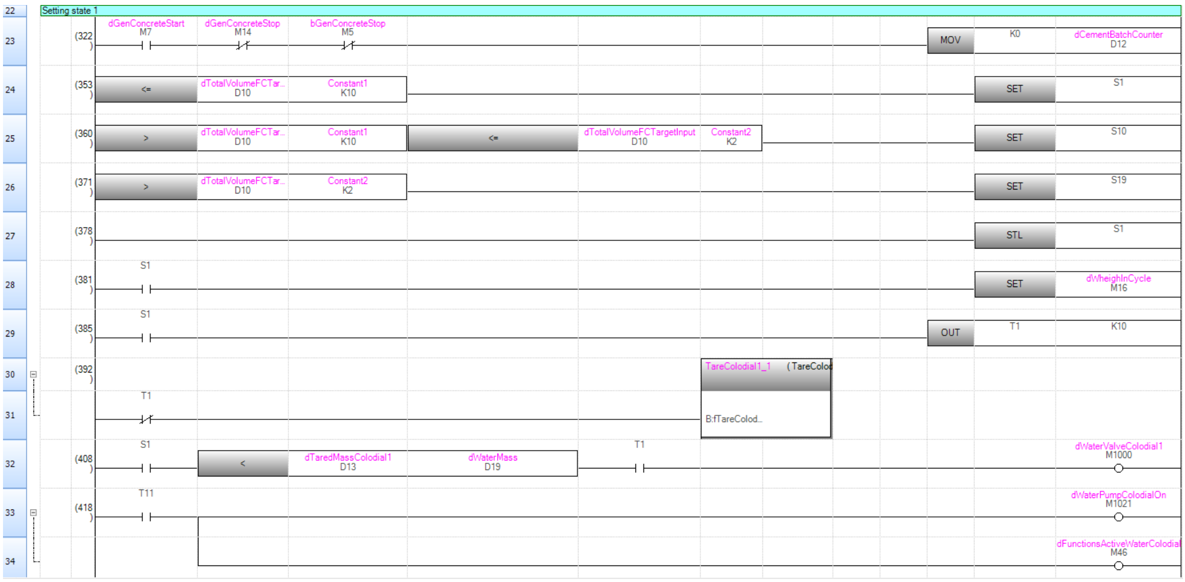


Figure 6, Ladder Diagram code, part of A-side production line. Displaying row 22-34/330.

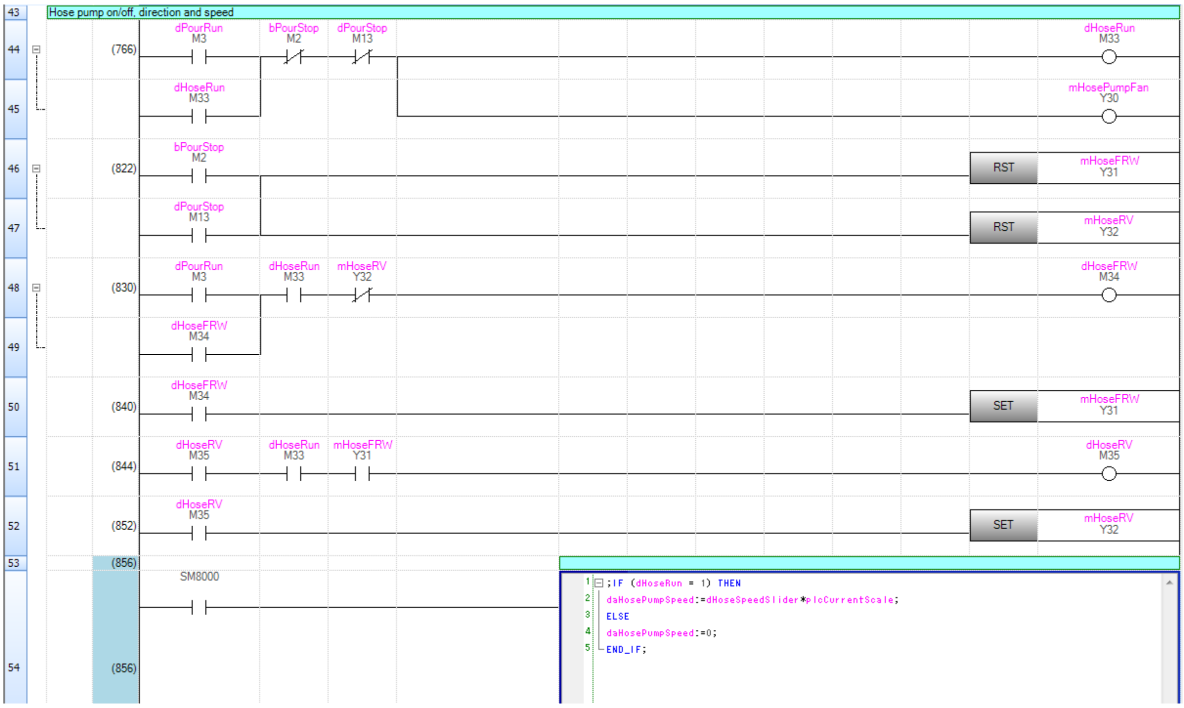
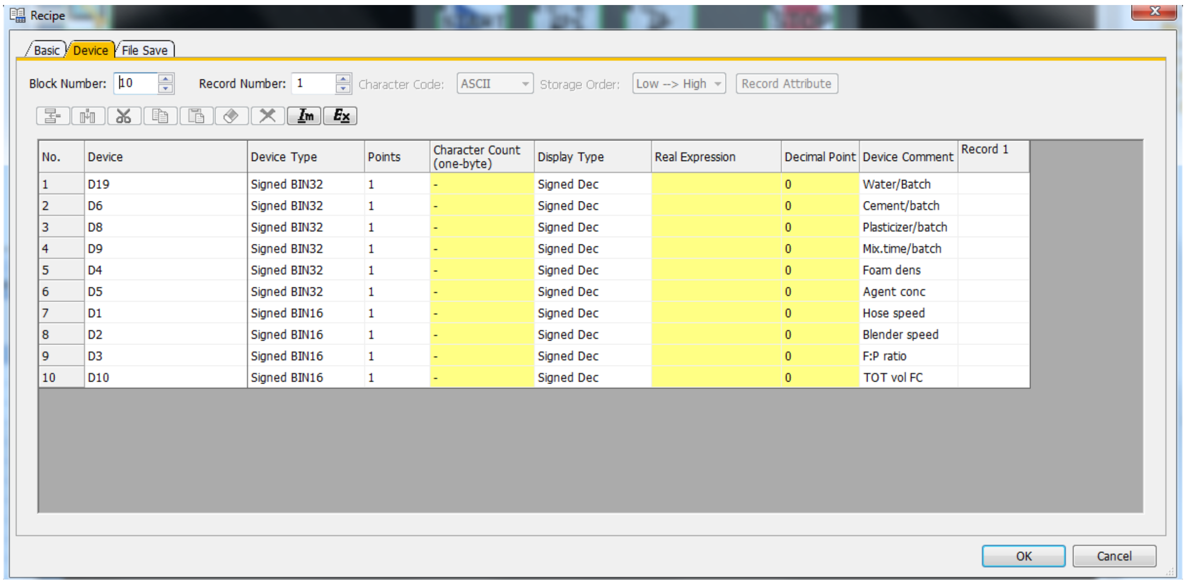


Figure 7, Ladder Diagram code, part of Machine-IO, with combined ST-block. Displaying row 43-54/60.

9.3 (2) Implementation of quality control functions.



Recipe

Basic | Device | File Save

Block Number: 10 Record Number: 1 Character Code: ASCII Storage Order: Low --> High Record Attribute

No.	Device	Device Type	Points	Character Count (one-byte)	Display Type	Real Expression	Decimal Point	Device Comment	Record 1
1	D19	Signed BIN32	1	-	Signed Dec		0	Water/Batch	
2	D6	Signed BIN32	1	-	Signed Dec		0	Cement/batch	
3	D8	Signed BIN32	1	-	Signed Dec		0	Plasticizer/batch	
4	D9	Signed BIN32	1	-	Signed Dec		0	Mix.time/batch	
5	D4	Signed BIN32	1	-	Signed Dec		0	Foam dens	
6	D5	Signed BIN32	1	-	Signed Dec		0	Agent conc	
7	D1	Signed BIN16	1	-	Signed Dec		0	Hose speed	
8	D2	Signed BIN16	1	-	Signed Dec		0	Blender speed	
9	D3	Signed BIN16	1	-	Signed Dec		0	F:P ratio	
10	D10	Signed BIN16	1	-	Signed Dec		0	TOT vol FC	

OK Cancel

Figure 8, Dialog window, GT Designer 3, displaying recipe parameters.

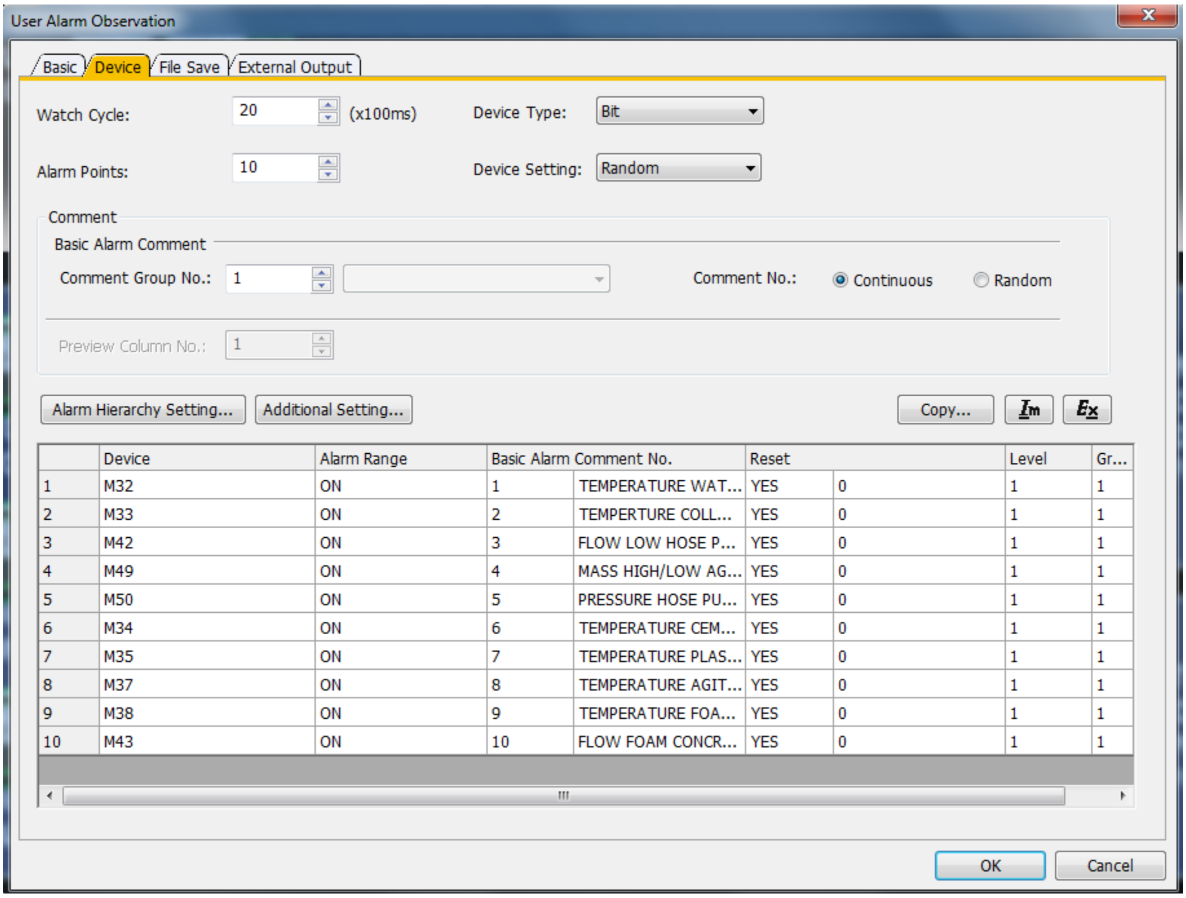


Figure 9, Dialog window, GT Designer 3, displaying alarm parameters.

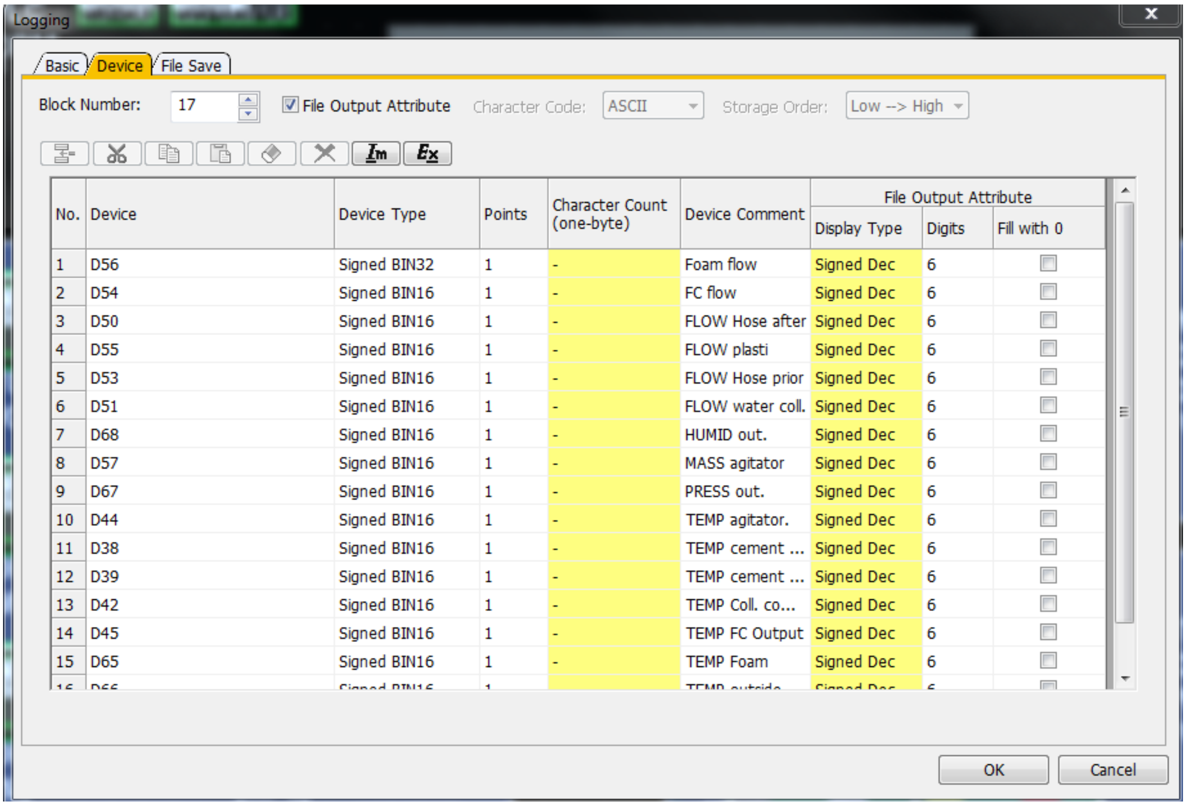


Figure 10, Dialog window, GT Designer 3, displaying logging parameters.

9.4 (3) Improved and implemented HMI functions.

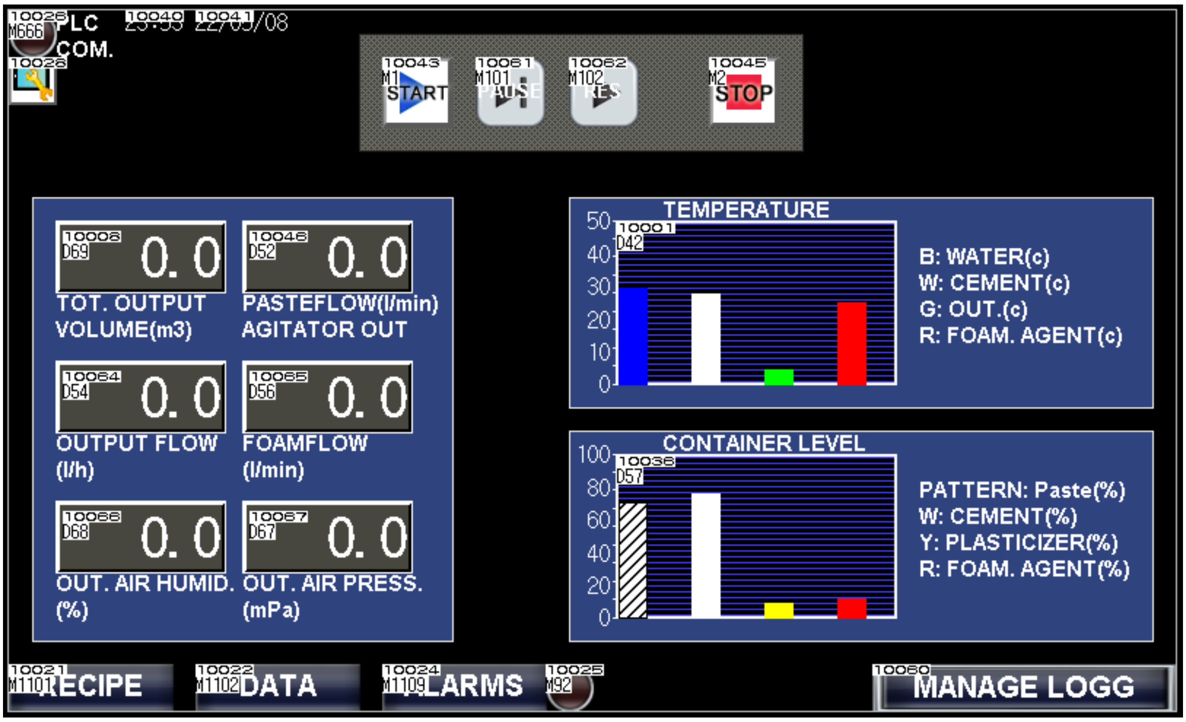


Figure 11, Screen, GT Designer 3, displaying home screen.

Figure 12, Screen, GT Designer 3, displaying recipe screen.

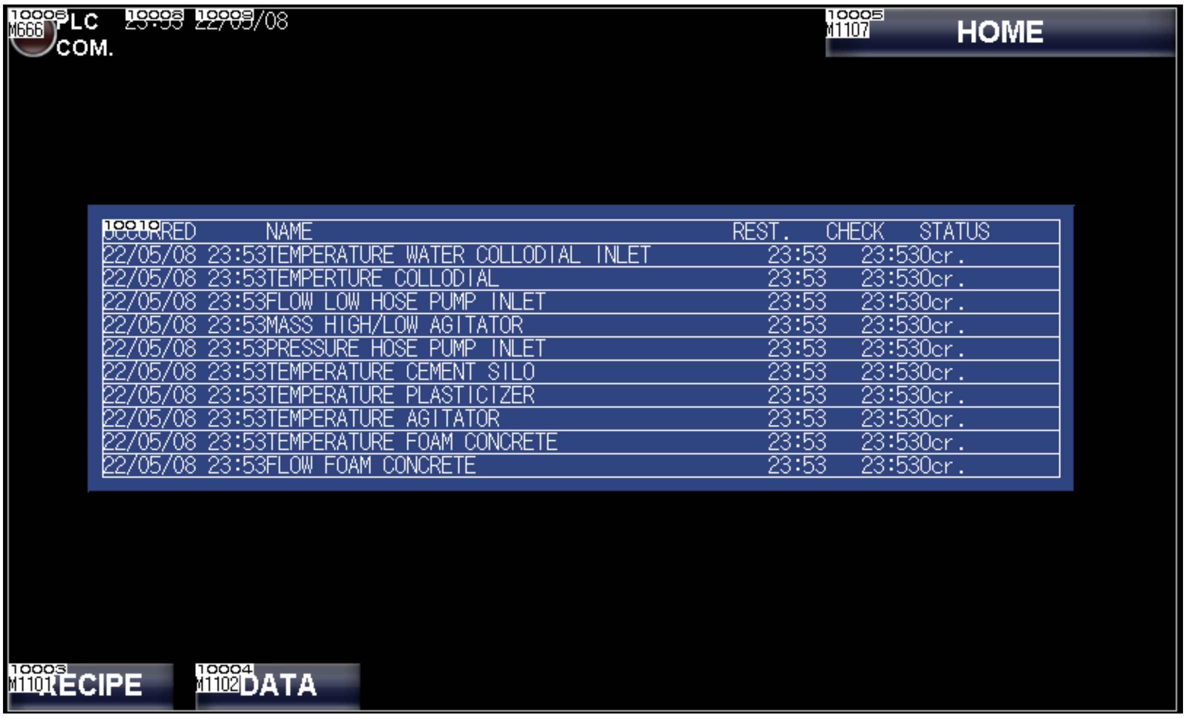


Figure 13, Screen, GT Designer 3, displaying alarm screen with interface.

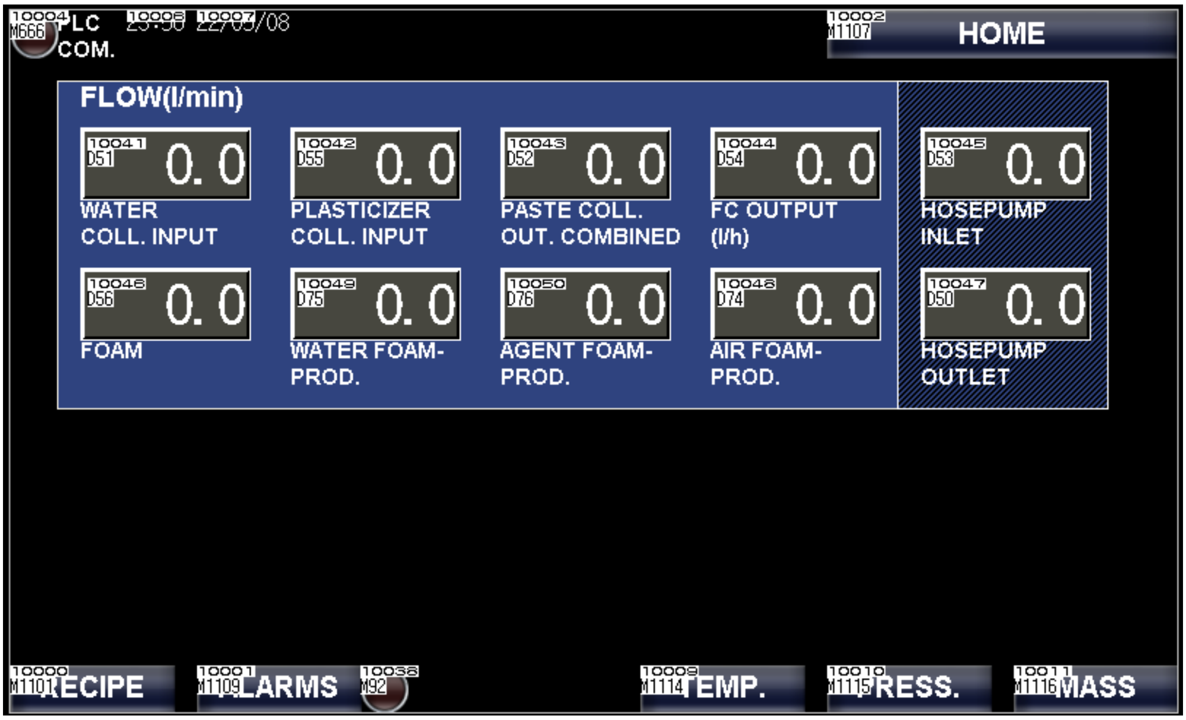


Figure 14, Screen, GT Designer 3, displaying data, flow screen.

Figure 15, Screen, GT Designer 3, displaying data, temperature screen.

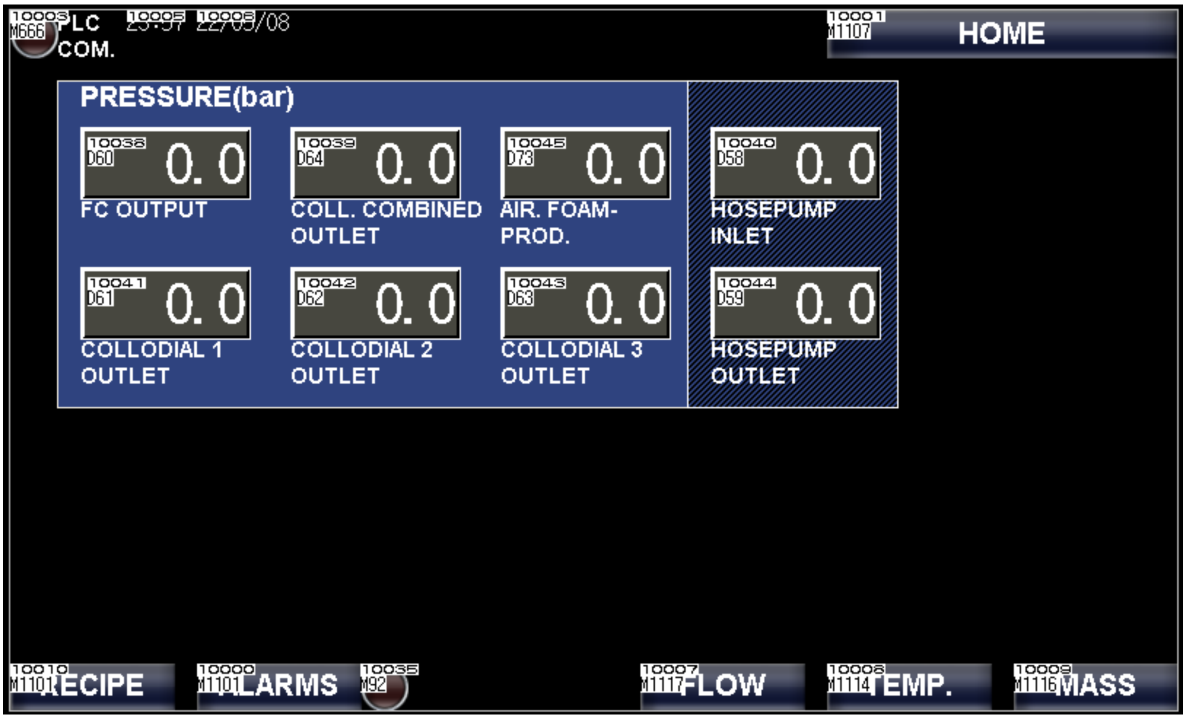


Figure 16, Screen, GT Designer 3, displaying data, pressure screen.

Figure 17, Screen, GT Designer 3, displaying data, mass screen.

9.5 Other

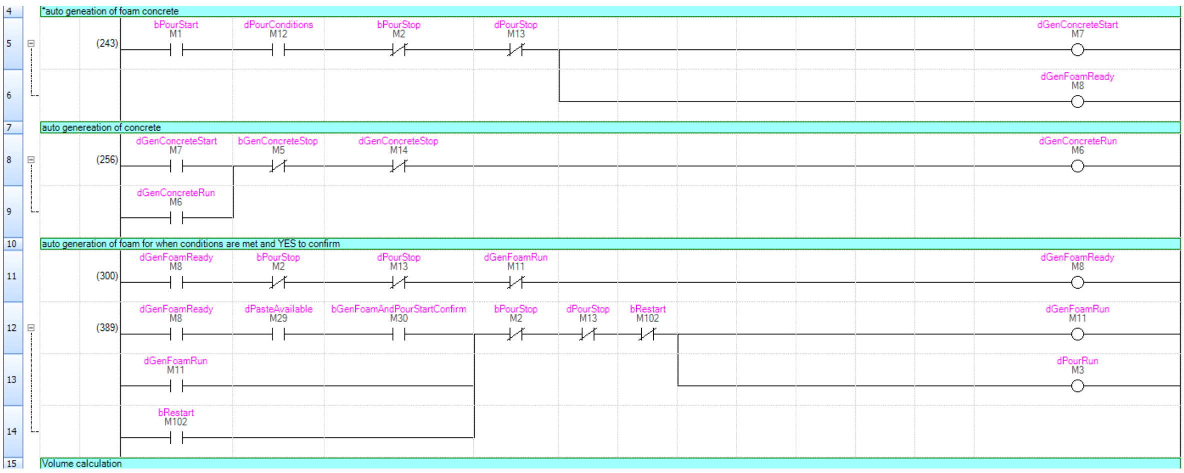


Figure 18, GX Works 3, Main-program.

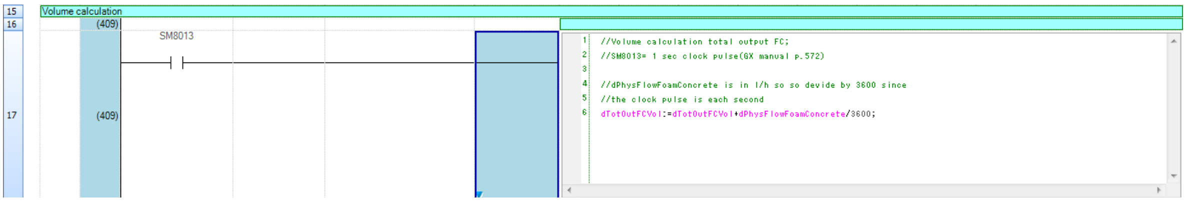


Figure 19, GX Works 3, Volume calculation based on flow over time.

Figure 20, GX Works 3, handling of AD-values.

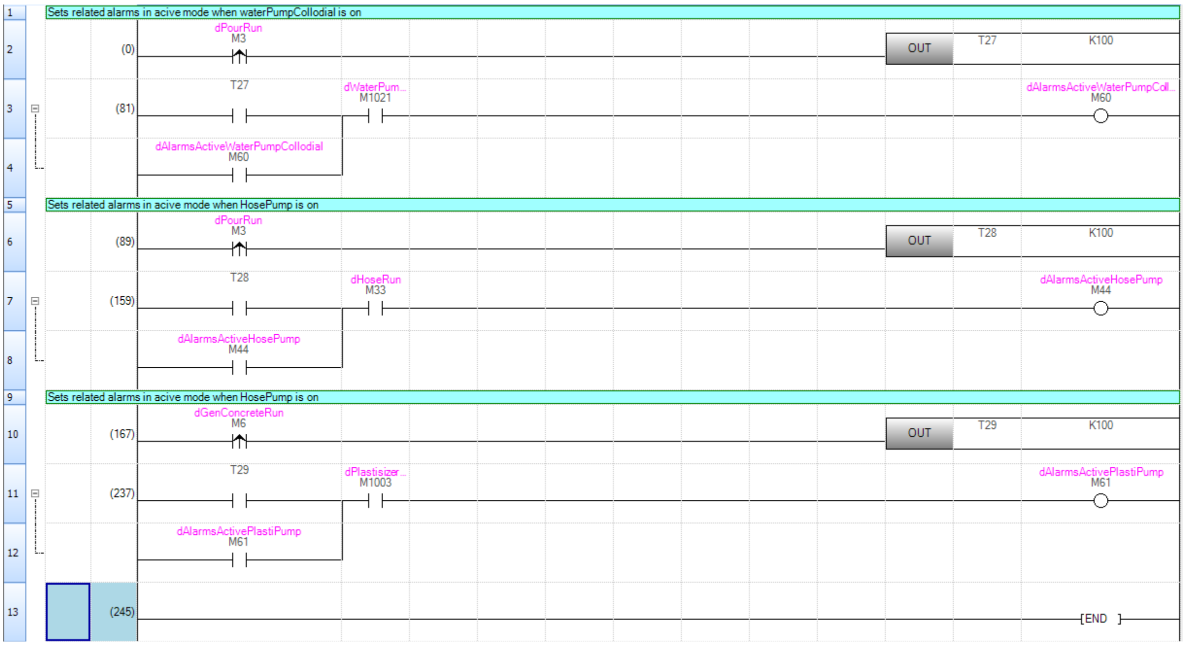


Figure 21, GX Works 3, alarms active based on process-state.

Figure 22, GX Works 3, tare-function example, called-upon function when necessary.

106	dPressAfterColodialCombinedAlert	Bit	...	VAR_GLOBAL	M56			Status bit for if preassure too high
107	dTempFoamAlert	Bit	...	VAR_GLOBAL	M57			Status bit for if temp too high/low
108	dMassCementSiloAlert	Bit	...	VAR_GLOBAL	M58			Status bit for if mass too high/low
109	dMassPlastiSiloAlert	Bit	...	VAR_GLOBAL	M59			Status bit for if mass too high/low
110	dPhysTempFoam	FLOAT [Single Precision]	...	VAR_GLOBAL	D65			Physical values(c) of temp after foam generator
111	dPhysMassCementSilo	FLOAT [Single Precision]	...	VAR_GLOBAL	D66			Physical values(kg) of mass in cement silo
112	dPhysMassPlastiSilo	FLOAT [Single Precision]	...	VAR_GLOBAL	D67			Physical values(kg) of mass in plasticixer silo
113	bPause	Bit	...	VAR_GLOBAL	M101			Pause-state for all operation

Figure 23, GX Works 3, label/device list example, displaying 106-113/ca.430.