



# The development of a control system for gravimetric feeding of a twin screw extruder

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## SUMMARY

The control of gravimetric feeding is generally done by control systems which utilize feedback control. The main problem with these control systems is that they generally revert to volumetric feeding during the *refilling cycle*. Furthermore the control system software is proprietary information and therefore not in the public sector and also very expensive. The main purpose of the study was therefore to review the basics of gravimetric feeding and to apply the knowledge in the design of a control system with applicable software for gravimetric feeding which is not affected by material bulk density variations, targeting food extrusion applications. It is also aimed at producing a test bench to test the control system and the developed software.

The developed control system is a programmable logic controller (PLC) based control system. This allows for the control system to be easily integrated into any PLC controlled twin screw extruder. The control system was extensively tested to verify the developed gravimetric control algorithms. The results from the experimental tests illustrated that a fully functional gravimetric feeding system had been developed. Most importantly also that the volumetric characteristics of a material can be used, to assist a PI-controlled gravimetric feeding system in both the *feeding cycle* and the *refilling cycle*.

*Keywords:* Gravimetric feeding; Extrusion; PLC; volumetric characteristics; control algorithms; PI-control

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## List of Abbreviations

AB	Allen Bradley
AC	Alternating current
A/D	Analog to digital
AFD	Adjustable frequency drive
BHL	Bin high level
BLL	Bin low level
CC	Calibration calculations
CHL	Calibration high level
CLL	Calibration low level
CP	Calibration process
CPU	Central processing unit
CV	Controlled variable
D/A	Digital to analog
DC	Direct current
FCE	Final control element
FSS	Fixed screw speed
GMU	Geared motor unit
GUI	Graphical user interface
GWC	Gravimetric weighing cycle
Hz	Hertz
I	Integral
I/O	Input / Output
LC	Load cell
LED	Light emission diode
LIW	Loss-in-weight
LUT	Loop update time
MA	Moving average
<i>ms</i>	Milliseconds
NWU	North-West University
P	Proportional
PC	Personal computer
PI	Proportional plus integral
PID	Proportional integral derivative
PLC	Programmable logic controller

PV	Process variable
PWC	Predicted weighing cycle
P&ID	Process and instrumentation diagram
rpm	Revolutions per minute
SISO	Single input single output
SP	Set point
VFD	Variable frequency drive
VSD	Variable speed drive

### List of Symbols

$e$	Error between CV and SP
$K_c$	Controller gain
$\Delta m_B, \Delta m_{B,MA}$	Actual weight loss ( $kg$ )
$\Delta m_{B,CHL}$	Actual weight loss calibration high level ( $kg$ )
$\Delta m_{B,CLL}$	Actual weight loss calibration low level ( $kg$ )
$m_B, m_{B,MA}$	Actual weight / Bin weight ( $kg$ )
$m_{B,CHL}$	Calibration bin high level ( $kg$ )
$m_{BHL}$	Bin high level ( $kg$ )
$m_{B,CLL}$	Calibration bin low level ( $kg$ )
$m_{BLL}$	Bin low level ( $kg$ )
$\dot{m}_G$	Gravimetric feed rate ( $kg/h$ )
$\dot{m}_I,$	Instantaneous / Volumetric feed rate ( $kg/h$ )
$P. O.$	Percentage overshoot (%)
$T_i$	Integral time / Reset term
$T_r$	Rise time ( $s$ )
$T_s$	Settling time ( $s$ )
$\Delta t$	Sampling rate ( $s$ )

## Chapter 1: INTRODUCTION

Chapter 1 provides introductory information on volumetric- and gravimetric feeding to emphasize the importance of gravimetric feeding in extrusion systems. The problem statement is then given, followed by the issues to be addressed and the methodology of the investigative and the design approach.

### 1.1 Background

In the modern food and feed industry there are two main methods of feeding which can be applied to a twin screw extruder. The two methods are volumetric- and gravimetric feeding and are mostly done with screw feeders, either a single- or a twin screw feeder. As extrusion is a continuous process, it requires a continuous stable feed rate (kg/h) which is not affected by material bulk density variations, mechanical vibrations and field disturbances (i.e. moving equipment colliding with the feeder).

When a feeder bin (hopper) is full, there will be a tendency for the material at the lower part of the bin, to be of a higher density than the material at the upper levels. This is due to the fact that the lower material is compressed by the material in the upper layers. Volumetric feeders can't recognize this density change as they simply discharge a certain volume per unit time (volumetric- / instantaneous feed rate). With a properly designed volumetric screw feeder a feeding accuracy (deviation from the desired feed rate) in the range of 2-5% is generally achieved. This is, however in most cases not an acceptable accuracy for extrusion processes.

The desired accuracy (better than  $\pm 2\%$ ) for extrusion processes can be achieved by a properly designed gravimetric feeding system. Gravimetric feeding systems achieve the desired accuracy by controlling the feeder screw speed to deliver a constant stable weight per unit (weight/unit) time as kg/hr (kilogram per hour) under industrial operating conditions.

Any feeder, whether being volumetric or gravimetric has a *feeding cycle* and a *refilling cycle* but no feed rate (instantaneous or gravimetric) can be measured during the *refilling cycle*. This imposes a great challenge for any gravimetric feeding control system. Maintaining feeding accuracy during the *refill cycle* is generally considered to be one of the most challenging design aspects of a gravimetric control system.

Simple gravimetric control systems revert to volumetric feeding (fixed screw speed) during the *refilling cycles*. This is achieved by locking the screw speed of the feeder at the last recorded value of the previous gravimetric feeding cycle, during refilling. With these simple gravimetric control systems, it is common to hear a sudden change in feeder speed at the end of the *refilling cycle* when the control system reverts to gravimetric feeding. The magnitude of this inaccuracy is dependent on the characteristics and absolute density of the material being handled.

## **1.2 Problem statement and Aim**

The control of gravimetric feeding is generally executed by complex control systems which utilize feedback control. The main problem with these control systems is that they are complex and the control system software is proprietary information and therefore not in the public domain and furthermore very expensive.

The aim of the study is to review the basics of gravimetric feeding and to apply the knowledge in the design of a control system with applicable software for gravimetric feeding which is not affected by material bulk density variations by making use of the material's volumetric feeding characteristics. It is also aimed at producing a test bench to test the control system's control abilities and the software developed.

## **1.3 Issues addressed**

The issues addressed in this study are as follows:

- Control system design specifications
- Feeding system:
  - Feeder
  - Supply system
- Hardware selection and procurement
- Manufacturing
- Control system software development
- System integration
- System evaluation

## 1.4 Research methodology

- **Control system design specifications:** The control system design specifications were created by assigning technical performance measures to the technical requirements as specified by the project sponsor. As the sponsor has only specified top level requirements (i.e. feed rate, feeding accuracy, what material to be fed etc.), an in depth literature survey was carried out to obtain the relevant requirements of a control system for an optimized gravimetric feeding system.
- **Feeding system:** A feeding system was designed following a literature survey on the basics of feeding systems and the requirements of gravimetric feeding.
- **Hardware selection and procurement:** Suppliers were selected and the required equipment for the project was sourced.
- **Control system software development:** After having completed the literature survey, the necessary control algorithms were devised and programmed to provide a user-specific gravimetric feeding control system.
- **Manufacturing:** Since it was not possible to manufacture all the necessary components of the gravimetric feeding system in-house, manufacturing drawings were sent to the contracted suppliers for manufacturing of some of the components (i.e. feeder bin, bulk storage bin, etc.). The remainder of the components and sub-systems were manufactured in-house.
- **System integration:** With the manufacturing and assembly of the test bench completed and the completion of the user program, these two systems were integrated in order to have a fully functional gravimetric feeding test bench available.
- **System evaluation:** The system was evaluated by comparing its gravimetric feeding capabilities to the design specifications of the system. Various tests were carried out to verify each sub-routine of the control program. Some of the aspects of the control system which were evaluated are the following:
  - Weighing system signal processing
  - Gravimetric feeding capabilities
  - Disturbance filtering

## 1.5 Overview of the dissertation

- *Chapter 2* presents an overview of findings of the literature survey on the basics of gravimetric feeding (for extrusion).
- *Chapter 3* presents a detailed description of the developed gravimetric feeding test bench which was designed and manufactured to evaluate the control system software.
- *Chapter 4* presents a detailed description of the control system software (user program) developed for gravimetric feeding of a twin screw extruder.
- *Chapter 5* presents a detailed discussion on the experimental verification of the developed gravimetric control algorithms.
- *Chapter 6* presents a summary of the most important conclusions drawn from this study and makes recommendations for future work, followed by a closure statement on the project.

## 1.6 Summary

Chapter 1 presents background on volumetric- and gravimetric feeding after which the problem statement is given. The issues that needed to be addressed are highlighted and the methodology that was followed is presented. A short overview of the structure of the dissertation is also included.

## Chapter 2: LITERATURE STUDY

Chapter 2 presents an overview of findings of the literature survey on the basics of gravimetric feeding (for extrusion).

### 2.1 Background

#### 2.1.1 Extrusion

A food extruder is a device that expedites the shaping and restructuring process for food ingredients. Extrusion is a highly versatile unit operation that can be applied to a variety of food processes. Extruders can be used to cook, form, mix, texturize, and shape food products under conditions that favour quality retention, high productivity, and low cost (Riaz, 2000).

#### 2.1.2 Feeding systems

Essential to any extrusion system is the quality of product delivery which is primarily determined by the mix of ingredients and the feed rate (also determining profitability). A feeding system for extruders in the food and feed industries almost always consists of three basic component sections. Figure 2-1 represents a very basic diagram of the feeding system component sections. Each of the three component sections are made up of an assembly of sub-components and applicable software.

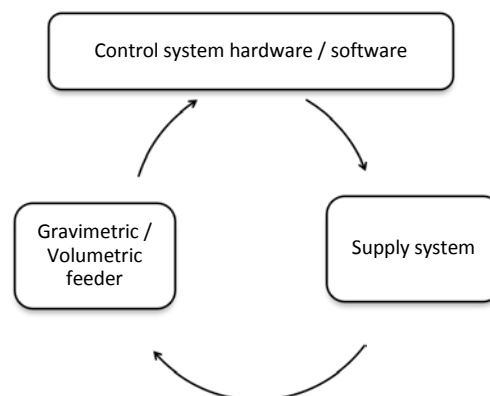


Figure 2-1: Feeding system components sections

Typically, the extrusion rates of food and feed extruders are controlled by a metering device or a feeder screw. Volumetric feeding of ingredients can be achieved through variable speed augers or screw conveyors. Loss-in-weight (gravimetric) feeding can be achieved by mounting the designed and manufactured feeder assembly on load cells. Vibratory-type

feeders having variable frequency or stroke can also be utilized as gravimetric devices (Riaz, 2007). Weight belts are also used to meter ingredients gravimetrically.

### **2.1.3 Gravimetric feeding**

A gravimetric feeder relies on weighing the material to achieve a required discharge/feed rate or batch weight. It can be said that a gravimetric feeder is a volumetric feeder on a scale with feedback control. This approach should be used when:

- Accuracy of less than  $\pm 2\%$  is required
- The material bulk density varies according to the percentage fill of the feeder bin.

Feed accuracy of  $\pm 0.5\%$  is sometimes obtainable with a properly designed gravimetric feeding system. There are basically two ways to feed gravimetrically, continuous or batch. Most production size extruders are continuous starve-fed devices where the throughput is governed by the dry feed delivery rate from the feeder screw to the extruder barrel (Riaz, 2000). For this reason the remainder of this study considers continuous feeding.

A continuous gravimetric feeding system controls the weight per unit (weight/unit) time as kg/hr (kilogram per hour) and a batch system simply controls the weight of material such as 50 kg of material from a mixer. Gravimetric feeding systems have become a standard for most extrusion processing systems.

## **2.2 Automated system control**

According to Tewari (2002), the word *control* used in everyday life refers to the act of producing a desired result. An example of everyday control is the household refrigerator. The temperature inside the refrigerator is controlled by a thermostat. Another example of control is a human driving a motor vehicle. While driving a motor vehicle, the driver controls the speed and the direction of the vehicle to reach the desired destination as quickly as possible, without hitting anything on the way. The list of every day system control is endless.

A study of control involves developing a mathematical model for each component of the control system. A system is a set of self-contained processes under study. Therefore, a *control system* by definition consists of the system to be controlled, called the *plant or process*, as well as the system which exercises control over the plant, called the *controller*. A controller could be either human, or an artificial device. The controller supplies the plant with

an *input* signal, called the *input to the plant*, in order to produce a desired response from the plant called the *output from the plant*. The terms *input* and *output* are used to describe the signal that goes into a system, and the signal that comes out of a system when referring to an isolated system (Tewari, 2002).

According to Shimmers (1992), control systems can be defined as devices which regulate the flow of energy, matter, or other sources. Their arrangement, complexity, and appearance vary with their purpose and function. In general, control systems can be categorized as being either open-loop or closed-loop. The distinguishing feature between these two types of control systems is the use of feedback comparison for closed-loop operation.

### 2.2.1 Open-loop control system

Open-loop control systems represent the simplest form of controlling devices (Shimmers, 1992). A control system is referred to as an open-loop system, when the control input is applied without any knowledge of the plant output. Figure 2-2 illustrates a *schematic block diagram* of an open-loop control system, where the subsystems (controller and plant) are shown as rectangular blocks. The arrows indicate the input and output of each subsystem.

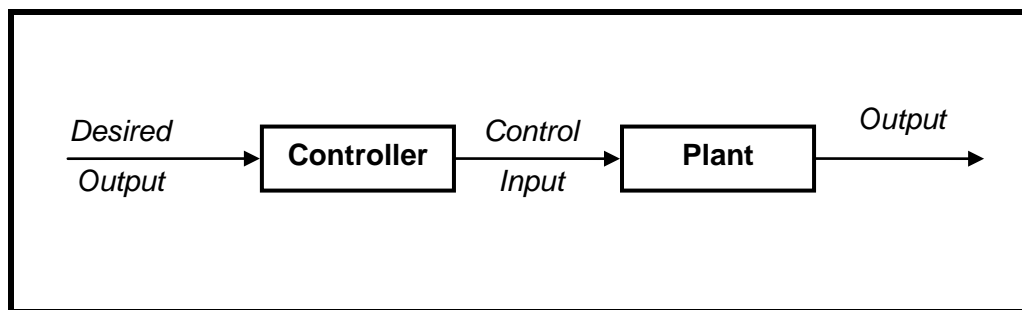


Figure 2-2: Open-loop control system (Schematic block diagram)

An open-loop (direct) system operates without feedback and directly generates the output in response to an input signal (Richard *et.al*, 2005). Open-loop control is therefore very difficult to apply to industrial systems. Open-loop control will only be successful if the controller has prior knowledge of the behaviour of the plant, which can be defined as the relationship between the control input and the plant output (Tewari, 2002). This is true for constant plant parameters, if the plant parameters or the operating conditions change, the control system will have to be recalibrated to suite the new conditions.

### 2.2.2 Closed-loop control system

According to Richard *et.al* (2005), a closed-loop system uses a measurement of the output signal in comparison with the desired output to generate an error (actuating) signal that is applied to the controller. Figure 2-3 illustrates a *block-diagram* of a closed-loop control system, which is a single-loop feedback system.

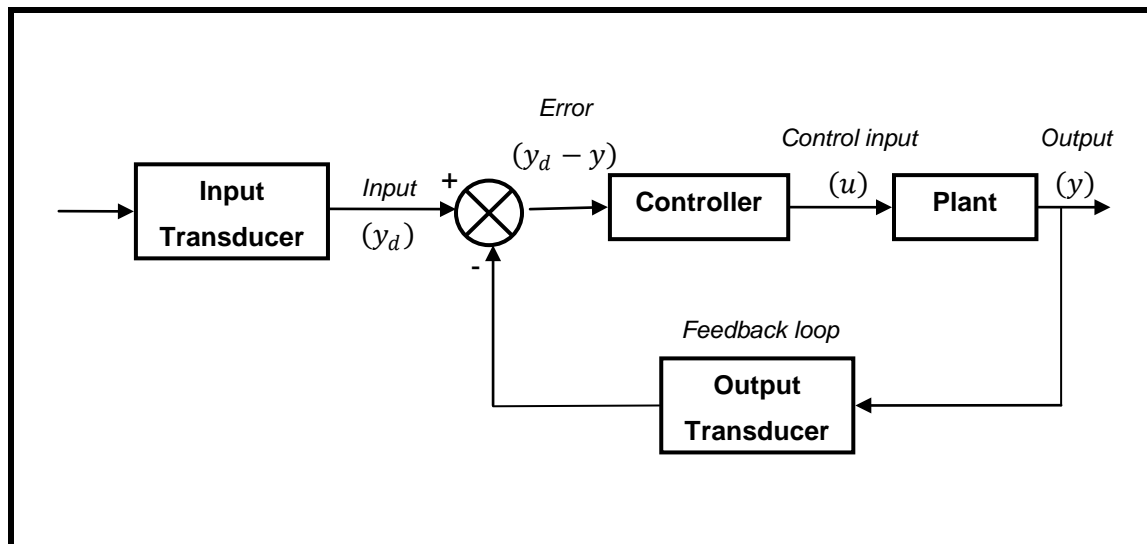


Figure 2-3: Closed single-loop control system (Schematic block diagram)

In Figure 2-3 there is an extra component in the system denoted by a circle before the controller block. This circle is called a *summing junction*; it algebraically adds the *input signal* ( $y_d$ ) to the *output signal* ( $y$ ), which arrives via the feedback loop. The feedback loop is the return path from the output to the summing junction. In Figure 2-3 the output signal is subtracted from the input signal. The result is generally called the *actuating signal*. The *actuating signal's* value is equal to the actual difference between the input and the output, in systems where both the input- and output transducers have unity gain. Unity gain means that the transducer amplifies its input by one. Under this condition, the actuating signal is called the *error* (Nise, 2004).

Closed-loop control systems are inherently dynamic according to Richard *et.al* (2005). Because of this, their performance is usually specified in terms of both the *transient response* and the *steady state response*. *Transient response* can be defined as the response that disappears with time. *Steady state response* can be defined as the response that exists for a long time following any input signal initiation.

According to Richard *et.al* (2005), the standard performance measures are defined in terms of the step response of a system as illustrated by Figure 2-4.

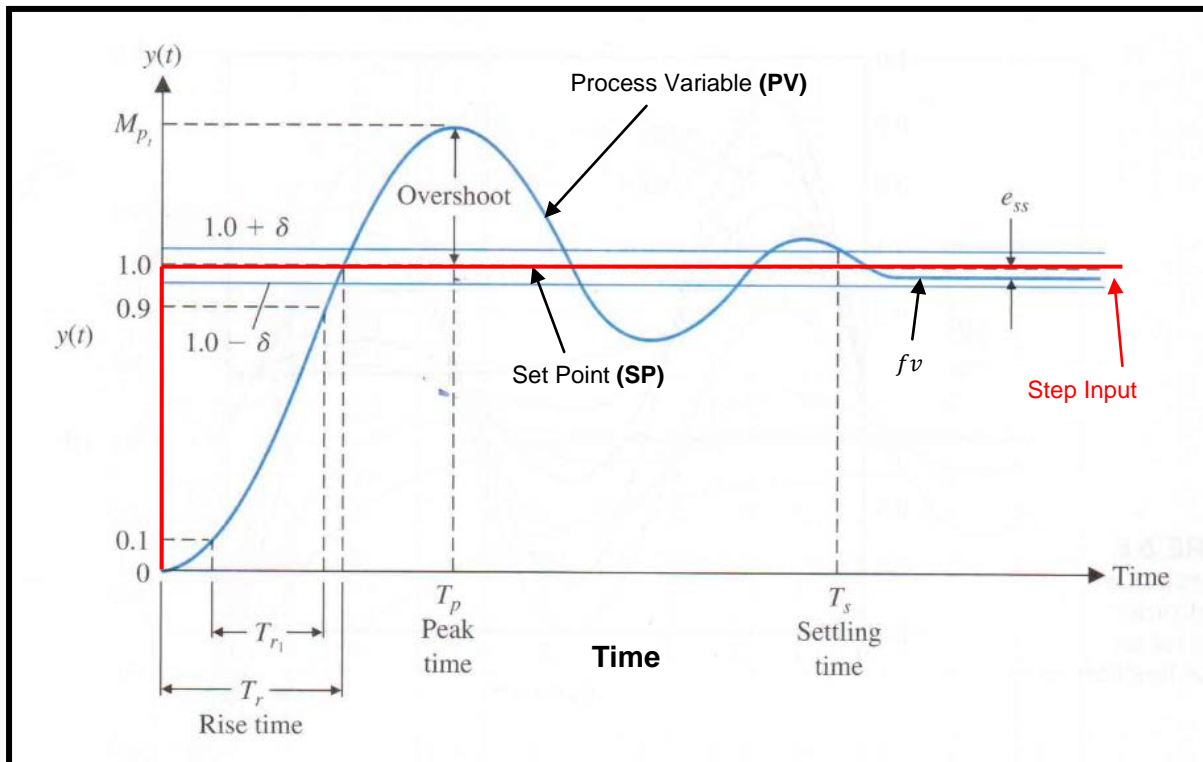


Figure 2-4: Step response of a feedback control system (Modified after Richard *et.al*, 2005)

Referring to Figure 2-4 a useful performance index for *under damped* systems with an overshoot, is the 0-100% rise time ( $T_r$ ). But for the purpose of this project, the interest lies in the similarity with which the actual response matches the step input as illustrated in Figure 2-4. This is normally measured by the *percent overshoot* (*P.O.*) and the *settling time* ( $T_s$ ). According to Richard *et.al* (2005), the percentage overshoot is defined as,

$$P.O. = \frac{M_{p_t} - fv}{fv} \cdot 100\% \quad (2.1)$$

for a step input, where  $M_{p_t}$  is the peak value of the time response and  $fv$  the final value of the response. The *settling time* ( $T_s$ ) can be defined as the time required for the system to settle to within 2% of the set-point value. Closed-loop control systems are less sensitive to noise, disturbances, and changes in the environment due to the feedback control. Therefore, for industrial automated systems it is better to make use of closed-loop systems rather than open-loop systems as greater accuracy can be achieved.

### 2.2.3 Definitions

In automated system control there are a lot of terms used for different variables. According to Svrcek *et.al* (2006), some of the most widely used terms in open-loop control and closed-loop (feedback) control can be defined as follows:

- *SISO system*: Single-input-single-output control system.
- *Process Variable (PV)*: Represents the variable that is important to maintain under control.
- *Set Point (SP)*: This value represents the desired value of the PV which is set on the operator interface.
- *Controlled Variable (CV)*: Is the measured value of the PV which is compared to the SP.
- *Error (e)*: This value is a measure of the difference between the PV and the SP.
- *Primary element*: The instrument/s in a control loop that is used to measure the process variables such as temperature, pressure etc.
- *Controller*: Is whose “control law” and tuning drives the corrective action and influence the response of the SISO system.
- *Final Control Element (FCE)*: The instrument in a control loop to which the controller output is attached and through which the controller exercise its influence on the PV.
- *Manipulated Variable (MV)*: Represents the variable in a process to which the PV is sensitive, and to which the FCE is attached.
- *Open-loop control*: By definition places the FCE in a fixed position, or a prescribed series of positions, with the expectation that nothing will change (i.e. there will be no disturbances) to cause the desired state of the system (SP) to drift (Svrcek *et.al*, 2006).

- *Closed-loop (Feedback) control*: By definition it works through measuring the PV and comparing it with the SP to generate an error. The error, conditioned by the controller type and tuning, drives appropriate changes to the FCE (and thus the MV) such that the PV is driven back in the direction of the SP (Svrcek *et.al*, 2006).
- *Capacitance*: Represents a system's ability to absorb or store mass or energy. According to Svrcek *et.al* (2006), capacitance may also be defined as the resistance of a system to the change of mass or energy stored in it, i.e. inertia.
- *Dead time*: This is a characteristic of a physical system that causes an input disturbance to be delayed in time, but unchanged in form (Svrcek *et.al*, 2006).
- *Offset*: The difference between the stabilized PV of a system and the SP.
- *Differential gap / Dead band*: This refers to on-off control and inside the dead band no control action takes place.
- *Proportional band*: This refers to proportional control and the range of the CV over which the controller output to the FCE will change by 100%.

## 2.3 Control system hardware

According to Svrcek *et.al* (2006), a modern SISO control system is comprised of the following components:

1. Primary elements (or sensors/transmitters)
2. Controllers
3. Final control elements
4. Processes (i.e. electric motor)

The control components of a system are very system specific as not all processes make use of the same control hardware. It is therefore very important to analyse and understand the feeding system to be designed in order to properly select control components.

### 2.3.1 Primary elements

Primary elements of a control system are the instruments used to measure the controlled variable (CV) in a process which also gives feedback to the controller. Some of the controlled variables to be measured are temperature, pressure, revolutions of an electric motor, feed rate of the gravimetric feeder, etc. Therefore, the primary elements of a gravimetric feeding system can be regarded as the weighing system. There are many different weighing systems available on the market today. Recent years have seen a drastic growth in load cell technology, thus load cells have become the preferred method of weighing for continuous industrial feeding systems.

A multi-load cell weighing system consists of three basic components, the load cells (1...n), junction box and load cell instrumentation. Figure 2-5 represents a schematic flow diagram of the weighing system's signal path. The junction box combines the signals from the load cells in parallel into one signal to be processed by the load cell instrumentation, as most instrumentation is only supplied with a single input channel. If only one load cell is being used by the weighing system the junction box is not required.

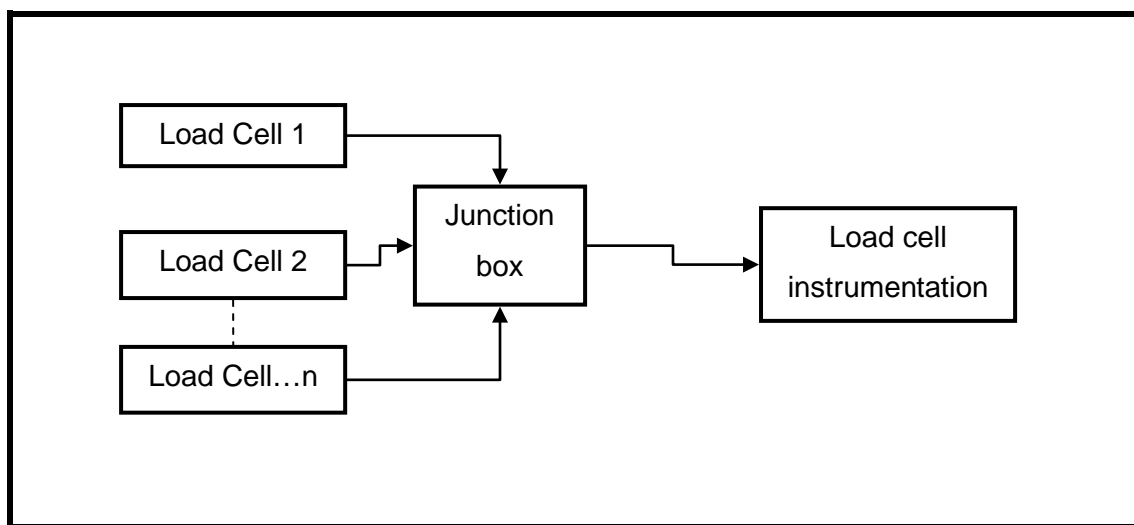


Figure 2-5: Schematic flow diagram of a multi-load cell weighing system signal path

### Load cells

Load cell technology is highly developed. The type of output signal generated by a load cell or the way to detect weight (bending, shear, compression, etc.) can be used to distinguish between load cell designs. Strain gauge load cells have become the method of choice for industrial weighing applications. This is not the only type of load cells available in the

industrial market today but the preferred type. Some other types of load cells operating on the basis of these generic names are:

- Hydraulic load cells, and
- pneumatic load cells

Strain gauge load cells convert the load acting on them into electrical signals. The gauges themselves are bound (with an adhesive) onto a beam or structural member that deforms when weight is applied. Maximum sensitivity and temperature compensation is in most cases obtained through the use of four strain gages (full bridge configuration). Two of the gages are usually in tension and two in compression. When weight is applied, the strain gives rise to a change in the electrical resistance of the gauges in proportion to the load.

When selecting a load cell for a specific application it should always be suitable for the operating environment. Different operating conditions require different load cell characteristics such as corrosion resistance, electrical safety, hose-down requirements, etc. Determining the total weight to be supported (gross weight) is the first step in a load cell selection process. The gross weight of a feeder for the food and feed industry consists of the net weight of the dry ingredients, the weight of the feeder bin and attached equipment (splitter gearbox, geared motor units, conveyer screws, etc.), and any weight that might be imposed on the bin by piping and/or conduits. The second step is to look at different types and designs of load cells to select the most suitable load cell type for the operating environment.

For continuous gravimetric feeding it is required that the weighing system be as steady as possible with minimal vibrations imposed on the load cell measuring devices, as any sudden movements or vibrations would interfere with the accuracy of the feed rate. This design requirement normally eliminates the use of one load cell for industrial weighing systems. If the selected amount of load cells is incorrect with wrong placement, then some load cells may be overloaded while the other load cells may carry less or no load at all. It is very important to take into account over-loading as it may very easily occur e.g., when a person steps on the feeder or weighing system during operation.

Figure 2-6 illustrates a schematic layout of a three-load-cell configuration that is used by most modern industrial weighing systems. Three points are selected for the stability effect

created by three load points and for the fact that the load will always be spread relatively even.

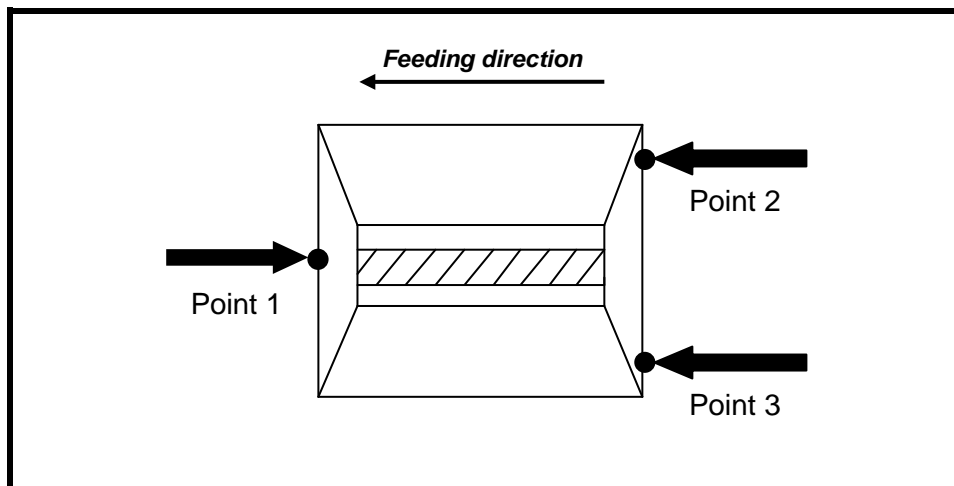


Figure 2-6: Schematic layout of a three-load-cell configuration showing a typical load cell placement option (Feeder bin top view)

### Load cell instrumentation

Load cell (digital weight) indicators are used to provide excitation to the cells, powering the strain gages and taking the output signal from the cells and converting it into a calibrated visual display e.g., kilograms. Optional with load cell indicators is an analogue output to a computer or a data acquisition system. Some indicators are built for general use while others are designed for a specific application or industry. Figure 2-7 shows a load cell indicator manufactured by Interface Inc., 2011.



Figure 2-7: 9860 TEDS High-Speed Indicator (Interface, 2011)

Depending on the manufacturer, a load cell indicator can either have a DC-supply or an AC-supply. The final decision whether to use a DC-supply or AC-supply lies with the project engineer, depending on the control system. Most load cell indicators available today, supply a DC voltage (excitation) to the load cells. Excitation voltages are normally between 5 and 15VDC, and are well regulated.

### 2.3.2 Controllers

High efficiency and high-quality production is the result of process automation. Day to day production tasks are rapidly progressing to fully automated systems, by making use of automatic control hardware. Safe and profitable operation of a system can be achieved by continually measuring process operation parameters. Some of the parameters are temperature, flows, pressures, levels, concentrations and weight.

These parameters can be used by controllers to automatically make process decisions, for example, actuating valves or pumps, controlling heaters, and actuating geared motor units, so that selected process measurements are maintained at desired values (Bayindir *et.al*, 2010). Figure 2-8 illustrates a very simple signal flow diagram of where the controller fits into the control system of a gravimetric feeding system.

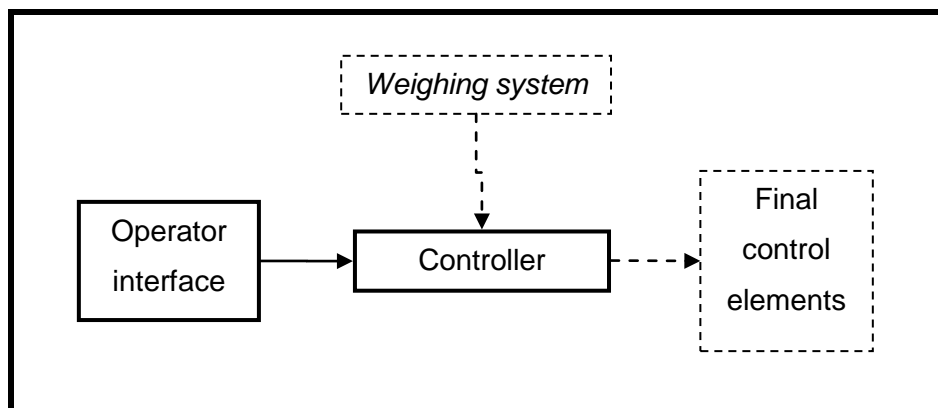


Figure 2-8: Automatic control signal flow diagram

The operator interface can either be a control panel, personal computer or a touch screen user interface. It is used to provide the process with process variables and control thereof. In most modern automated feeding systems the preferred controller is the Programmable Logic Controller (PLC). The PLC processes all the inputs from the user interface and the weighing system and makes the necessary process changes to the final control elements of the system. In a gravimetric feeding system the final control element controlled by the PLC is a variable speed drive (VSD). The VSD then controls the electric motor of the feeder.

## Programmable logic controller (PLC)

According to the National Electrical Manufacturing Association (NEMA), a programmable logic controller (PLC) is a digitally operated electronic system, designed for use in an industrial environment, which uses a programmable memory for the internal storage of user-orientated instructions (user program) for implementing specific functions such as logic, sequencing, timing, counting, and arithmetic to control, through digital or analogue inputs and outputs, various types of machines or processes. Both the PLC and its associated peripherals are designed so that they can be easily integrated into an industrial control system and easily used in all their intended functions (Dunning, 2006).

A hand-held programmer or a computer (personal or industrial) can be used to create user programs for PLC's. After the entire user program has been developed, entered and verified for correctness, the next step would be to transfer the program into the PLC's processor memory. When a PLC user program gets transferred from a personal computer's memory to PLC memory it is called *downloading* the program. Before a user program can be downloaded to a processor, the processor must be in *program mode*.

After downloading of the user program is complete and all inputs and output signals are wired to the correct screw terminals, the processor can be put in *run mode*. When in run mode, the programmed instructions will continuously run and solve incoming signals. Solving the programmed instructions is sometimes called solving the logic. Figure 2-9 illustrates an Allen-Bradley MicroLogix 1400 Controller by Rockwell Automation, Inc.



Figure 2-9: Allen-Bradley MicroLogix 1400 Controller (Rockwell Automation, 2011a)

## Operator interface

The interface between a process or machine and the operator is the primary means for providing dialogue and for introducing human judgment into an otherwise automatic system.

Signals arrive at the interface and leave the interface at electronic speed once an operator's judgement is made. The operator responds at a much slower communication rate. Because of the human limitations of an operator, the operator can be seen as a major bottleneck in the overall system. The interface, whether it takes the form of a console, a workstation, or other configuration, must be designed with the principle objective of shortening operator response time (McMillan *et.al*, 2004).

The type of interface used in a process or machine must be customized to the operator or operators. Also, training programs have to be in place to familiarise the operator or operators with the interface. Therefore the interface designer must also consider the software and not just the hardware. The interface forms an integral part of a process and therefore cost cutting at the interface level of a system carries large risks of later problems and dissatisfaction (McMillan *et.al*, 2004).

As processing- and manufacturing plants became more complex and larger the conventional complex control panel was no longer adequate enough. With the electrical-, design-, mechanical- and manufacturing technologies improving and developing, new control technologies were developed. Newer technologies made it possible to simplify operator interfaces. The latest technology in operator interfaces is computer based touch screen operator panels.

There are many different manufacturers, designs and types of graphical terminals available today. Figure 2-10 illustrates the Allen-Bradley family of PanelView Plus terminals produced by Rockwell Automation, Inc. These terminals give an operator a clear view into monitoring and controlling applications. If incorporated correctly, with the use of the right technologies, an entire plant's operator interface can be simplified with these terminals and/or similar terminals.



**Figure 2-10: PanelView Plus Terminals** (Rockwell Automation, 2011b)

### 2.3.3 Final control elements

A final control element (FCE) can be termed as a device that receives instructions from a controller and changes the state of the control system to achieve or sustain the desired set point (SP). The final control element of a gravimetric feeding system is a VSD which is attached to the feeder's electric motor. A VSD is a piece of equipment that regulates the speed and rotational force, or torque output, of an electrical motor. Variable speed drives are also known as variable-frequency drives (VFD), adjustable-frequency drives (AFD), AC drives, micro-drives or inverter drives. Figure 2-11 illustrates a PowerFlex 40 AC drive produced by Rockwell Automation, Inc.



Figure 2-11: PowerFlex 40 AC drive (Rockwell Automation, 2011c)

## 2.4 Control system software

Control software is just as important as the control hardware in automatic industrial systems, as this forms the heart of any automated system. The four main components of control system software is the programming interface, the programming software, the user program and the control mode of the system.

### 2.4.1 Programming interface

In today's modern control industry there are multiple ways of programming a PLC. According to Dunning (2006) a PLC can be programmed with:

- Hand-held programmer → Dumb programming terminal
- Smart programming terminal

- Personal computer
  - Desktop
  - Notebook (Laptop)
  - Windows CE based hand-held personal computers
  
- Industrial computers
  - Panel-mount
  - Rack-mount

Operating conditions of the PLC plays the main role in deciding which programming interface to be used by a plant or factory. It is therefore important to have some basic knowledge of the different programming interfaces available. When using a personal- or industrial computer to develop the user ladder program, a PLC ladder development software package is required.

A desktop PC and PLC's CPU can be connected serially through a serial cable connection, connected with a hardware interface between the computer's COM port and the PLC controller, or connected through a hardware interface card. The simplest connection method of the three is the serial connection (Dunning, 2006).

#### **2.4.2 Programming software**

PLC software is specifically designed to program a certain family of PLC's from a specific manufacturer. Most of the PLC program development software packages are manufacturer specific. One manufacturer's software packages will not allow a user to develop programs for another manufacturer's PLC's. Such PLC systems are referred to as *closed systems*. Modern PLC program development software has the ability to streamline troubleshooting through built-in search functions and forcing *input and output (I/O)* features (Dunning, 2006).

According to Dunning (2006), a group of technical experts were commissioned in 1979 to develop the first draft of a comprehensive programmable controller standard. What they basically set out to do was to create an *open PLC system*. In other words, this standard would attempt to standardize PLC programming and consequently make programs developed on one system usable on other PLC platforms with minimum modification. The committee issued the first draft of the standardization in 1982 and it is now known as IEC 1131. The IEC 1131 standard for programmable controllers comprises five parts (Dunning, 2006):

- Part 1: General Information
- Part 2: Hardware Requirements
- Part 3: Programming Languages
- Part 4: User Guidelines
- Part 5: Communication

Programming languages, the third part of the standard, has attracted the most attention from the international community.

### **The IEC 1131 - 3 Programming Standard**

The IEC 1131-3 programming standard defines a consistent set of programming languages for programmable controllers. The specification consists of four traditional languages and one higher level programming language. According to Dunning (2006), the five programming languages covered by the IEC 1131-3 standard can be divided into three groups:

- Graphical → Ladder Diagram Language  
→ Functional Block Diagram Language
- Text-based → Instruction List Language  
→ Structured Text Language
- Sequential Function Chart Programming Language

The type of PLC used will determine which programming language can be used. Newer PLC's can be programmed through more than one language. An example of a modern PLC program development software package is RSLogix 500.

#### **2.4.3 Basic control modes**

As automatic control of industrial systems has developed drastically in the last few decades, various methods of control or algorithms have been developed for feedback control systems. According to Svrcek *et.al* (2006), these basic control modes include:

- On/Off control
- Proportional control (P-only)
- Integral control (I-only)

- Proportional plus Integral control (PI-control)
- Derivative action (D)
- Proportional plus Derivative control (PD-control)
- Proportional Integral Derivative control (PID-control)

These control modes all have one thing in common, normally to improve the control system on which they are installed by reducing the offset, shortening response time, improve stability, etc. The following discussion is intended to provide a brief overview of these control modes but it will mainly focus on proportional control, integral control and proportional plus integral control.

### **Proportional control (P-only)**

Proportional control is a continuous control mode which is used in control systems. It is also the simplest control mode used to damp out oscillation in feedback control loops. This control mode normally stops the process variable (PV) from cycling around the set point (SP), but does not necessarily return the PV to the SP (Svrcek *et.al*, 2006).

The manipulated variable (MV) of a proportional controller is always proportional to the error ( $e$ ). According to Svrcek (2006), the error can be described as the deviation of the controlled variable (CV) from the SP. The MV of a proportional controller which is sent to the final control element (FCE) of a feedback control loop can be expressed by the following equation,

$$MV = K_c \cdot e \quad (2.2)$$

with  $K_c$ , the controller gain and  $e$ , the error. In (2.2):

$$e = SP - CV \quad \text{for reverse acting control}$$

or

$$e = CV - SP \quad \text{for direct acting control}$$

In general, a great advantage of proportional controllers is their fast response time when compared with other controllers. The down side of proportional controllers is that a sustained error (offset) occurs where the PV does not return to the SP even when steady state is reached. This is undesirable in most cases where automatic control is applied. Thus it is

normally required to combine proportional control with one of the other basic control modes to eliminate the offset.

### Integral control (I-only)

The action of *integral control* is to remove any error that may exist between the PV and SP of a system. According to Svrcek *et.al* (2006), as long as there is an error present, the output of this mode continues to move the final control element (FCE) in a direction to eliminate the error. The equation for integral control can be written as,

$$MV = \frac{1}{T_i} \int e.dt + MV_0 \quad (2.3)$$

The last term in (2.3)  $MV_0$  can be defined as, either the controller output before integration, the initial condition at time zero, or the condition when the controller is switched into automatic. In (2.3) the term  $T_i$  is the integral time of the integral controller. The integral time can thus be defined as the amount of time it takes the controller output (MV) to change by an amount equal to the error ( $e$ ). In other words, it is the amount of time required by the controller to duplicate the error (Svrcek *et.al*, 2006). Figure 2-12 illustrates the block diagram of an integral-only controller.

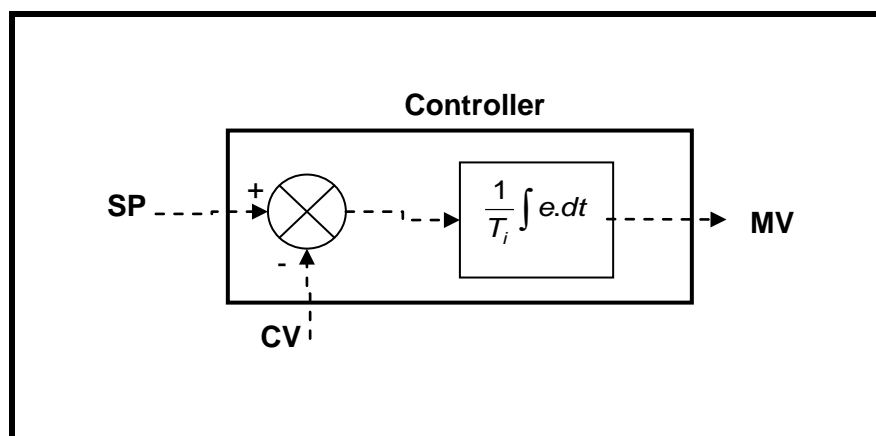


Figure 2-12: Integral-only controller block diagram

Figure 2-13 illustrates the different responses of P-only, I-only and PI controllers to a step input. An integral-only controller provides the advantage of eliminating offset, but it has a very slow response time. The response time of an integral-only controller is much slower than that of a proportional-only controller as illustrated in Figure 2-13. According to Svrcek

*et.al* (2006), the response period of an integral-only controller can be up to 10 times longer than that of a proportional-only controller.

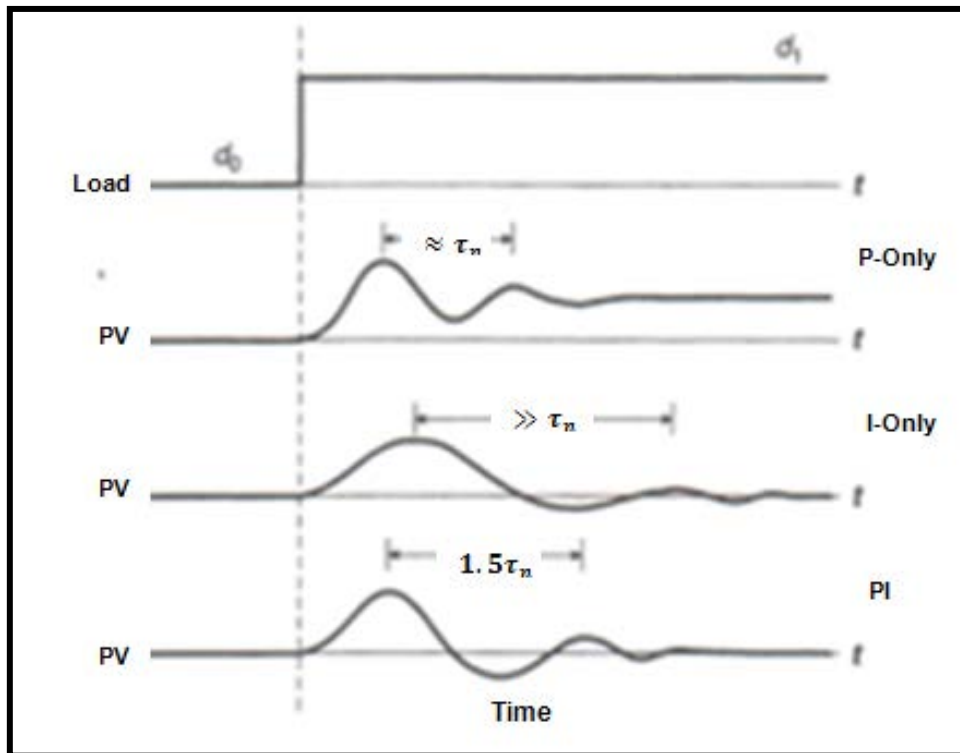


Figure 2-13: P-only, I-only and PI controller's responses where  $\tau_n$  equals the natural frequency of the system being controlled (Modified after Svrcek *et.al*, 2006)

Thus a trade off is made when an integral-only controller is used. If no offset is required by a system, then a slower period of response must be tolerated by the system when using an integral-only controller. If the requirement is a zero offset, and a faster response time is necessary, then the controller must be composed of both proportional and integral action (Svrcek *et.al*, 2006).

### Proportional plus integral (PI) control

A *proportional plus integral controller* provides a response period which is longer than a proportional-only controller but much shorter than an integral-only controller as illustrated in Figure 2-13. According to Svrcek *et.al* (2006), the response period of a process variable under proportional plus integral control is approximately 50% longer than a process variable under proportional-only control. As the response period of PI-control is much faster than I-only control, and only somewhat longer than P-only control, it is the preferred method of control in industrial applications. The equation for a proportional plus integral controller is as follows,

$$MV = K_c \cdot e + K_c \cdot \frac{1}{T_i} \int e \cdot dt \quad (2.4)$$

The PI controller gain ( $K_c$ ) has an effect not only on the error as seen previously, but also on the integral action as illustrated by (2.4). The integral action provides a bias that is automatically adjusted to eliminate any error (Svrcek *et.al*, 2006).

#### 2.4.4 Control mode selection

The form of control chosen must suite the application and be as simple as possible to achieve the desired results consistently. Figure 2-14 graphically outlines a procedure for control mode selection. According to Svrcek *et.al* (2006), starting at the top of the flow diagram, the first decision block asks the question: ‘Can offset be tolerated?’ If the answer is yes, then proportional-only control can be used. If the answer is no, then proceed to the next block which asks: ‘Is there noise present?’ If there is noise present then PI-control must be used. If there is no noise present, it is required to proceed to the next block.

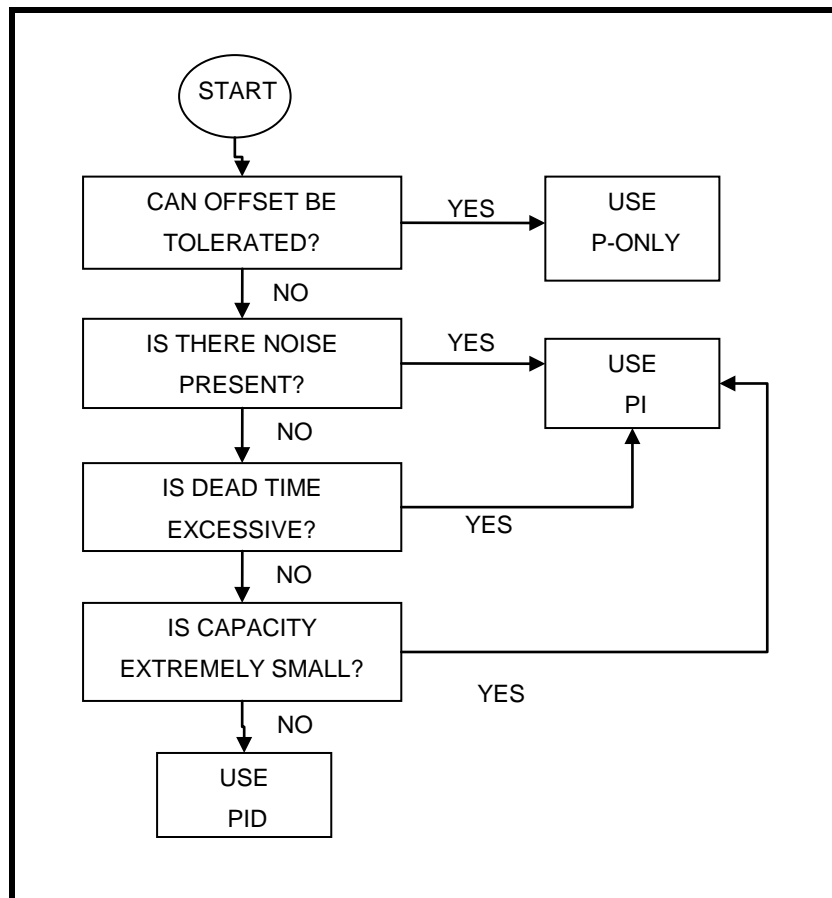


Figure 2-14: Flow chart for controller selection (Modified after Svrcek *et.al*, 2006)

The next block is the one, which asks: 'Is dead time excessive?' If the ratio of the dead time to the process time constant is greater than 0.5, then the process can be assumed to be dead-time dominant and therefore requires PI-control. If the process has no excessive dead time, then the next block asks: 'Is the capacitance extremely small?' If the answer is yes, then PI-control can be used (Svrcek *et.al*, 2006).

A process with a short dead time and small capacitance does not require derivate action to speed up the response since it is already fast enough, as is the case for a flow loop. Finally, if the process capacitance is large, then PID-control can be used. There are three possible paths to PI-control, whereas there are four decision blocks that must be passed through to reach PID-control (Svrcek *et.al*, 2006).

To ultimately control any automated mechanical system *proportional integral derivative (PID) control* should be installed. The addition of the derivative mode in PID control provides a response period that is much the same as that of a proportional only (P-only) control with no offset, due to the integral action. Therefore, *derivative action* is added to overcome lags in a control loop. According to Svrcek *et.al* (2006), PID-control provides a tight dynamic response, but due to the derivative action it cannot be used in any process in which noise is anticipated.

## **2.5 Summary**

All the main components contained in the control system of a gravimetric feeding system were discussed in detail and the knowledge has been used to select components in the design of the control system of importance to this study.

## Chapter 3: GRAVIMETRIC TEST BENCH DESIGN

Chapter 3 presents a detailed description of the developed gravimetric feeding test bench which was developed to evaluate the control system software.

### 3.1 Design Layout

Having considered the knowledge obtained from the literature survey, a design layout of the test bench was created as presented in Figure 3-1. This schematic layout was used as a basis to further design the entire control system.

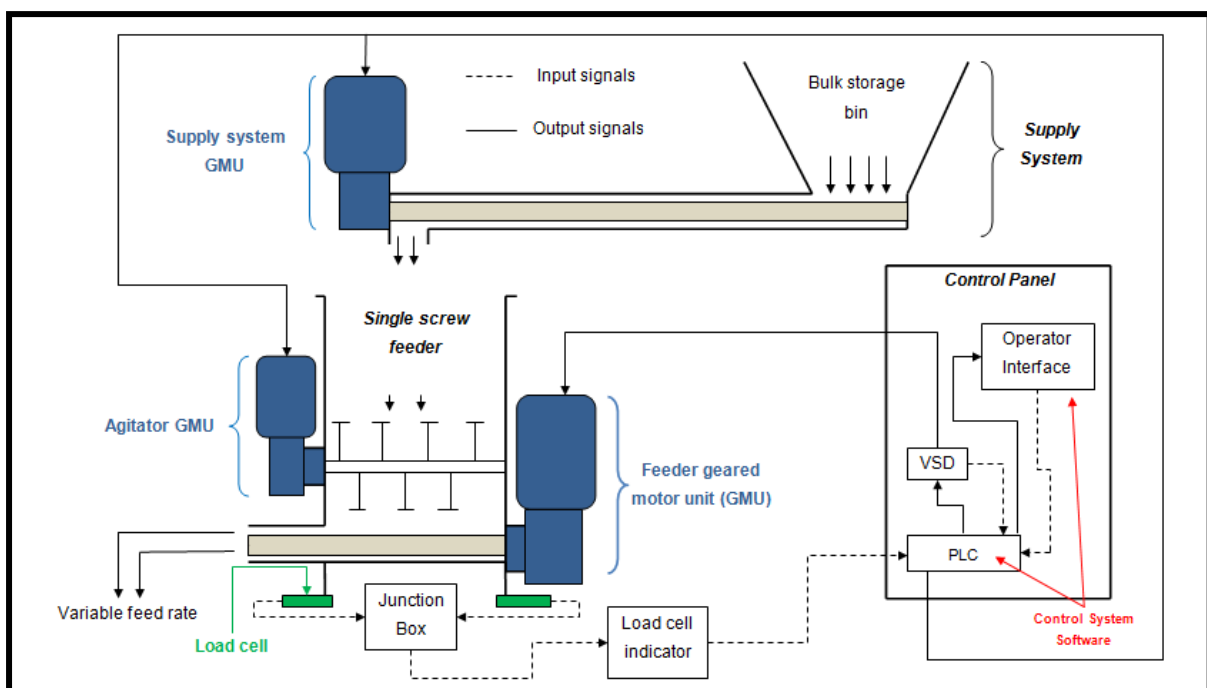


Figure 3-1: Gravimetric test bench conceptual layout

Illustrated below are the main component sections of the gravimetric feeding test bench layout, as presented in Figure 3-1.

- *Feeding system*
  - Feeder & Agitator
  - Supply system
  
- *Control system hardware*
  - Primary elements: Weighing system
  - Controllers: PLC
  - I/O modules
  - Operator interface

- Final control element: VSD
- Processes: Electric motor
- *Control system software*
  - User program
  - Graphical user interface (GUI)
  - Control mode

## 3.2 Design specifications

### 3.2.1 Control system and applicable software

A gravimetric feeding system generally has a manual- and automatic operating mode. Therefore an operator will be able to operate the test bench manually- or automatically from the *operator interface* utilizing the same PLC based control system. The difference between manual- and automatic operation of a gravimetric feeding system lies in the control system software (user program). Thus the same control system is used, but different paths (control algorithms) in the user program (control system software) are selected.

#### Manual Operation

The control system must allow for the feeder bin to be manually filled from a bulk storage bin with an auger, before the feeder can be started. The auger filling the feeder bin must stop automatically when the feeder bin has reached its desired weight (*bin high level*). The operator must also be able to start and stop the feeder bin agitator manually and the feeder must feed volumetrically (fixed screw speed) when feeding in the manual mode. The control system must contain a high- and low level for the feeder bin to automatically stop and start the supply system as needed.

#### Automatic Operation

As extrusion is a continuous process, the most important design specification of this specific operation mode is to ensure that a uniform stable gravimetric feed rate to within 2% of the desired value is achieved. This basically means that the control system must contain a weighing system with automatic feedback control which is not affected by material bulk density variations for both the feeding- and refilling cycles. When being used in automatic mode all of the necessary components to make the control system operate must be controlled automatically.

### **3.2.2 Feeding system**

#### **Single screw feeder**

The feeder must be installed with a floating single screw which delivers a maximum feed rate of  $\pm 300 \text{ kg/h}$  when feeding material with a bulk density of  $\pm 650 \text{ kg/m}^3$ , with the FSS set at 100% of the range of the selected geared motor unit (GMU). Furthermore, the feeder bin must be able to hold a maximum weight of  $\pm 60 \text{ kg}$  of a material with the above-mentioned density.

#### **Supply system**

The supply system must deliver a maximum feed rate of  $\pm 1500 \text{ kg/h}$  when feeding with a material with a bulk density of  $\pm 650 \text{ kg/m}^3$ . Furthermore, the bulk storage bin of the supply system must be able to hold a maximum weight of  $\pm 80 \text{ kg}$  of a material with the above mentioned density. The supply system must also be compact and mobile to allow for easy storage.

## **3.3 Feeding system**

When designing a feeder bin, or in fact any bin; the greatest challenge is to overcome *bridging*. Bridging is a term used for when the product in a bin stops flowing downwards into the screws or auger due to the interlocking of material particles. Several methods have been developed in the past few decades to overcome bridging. Probably the two most popular devices used to overcome bridging, is an *agitator* or a *vibratory device*. The feeding process and/or the raw material/product will determine which method can be applied to the bin. Therefore, when designing a bin it is very important to review the flow characteristic of the raw material being processed.

### **3.3.1 Single screw feeder**

Figure 3-2 illustrates a 3D model of the developed single screw feeder mounted on the weighing platform. In attempt to overcome bridging, the feeder bin's design was adapted to the flow characteristics of the raw materials processed and by provision of an agitator. Also shown in Figure 3-2, is the provision of a *floating single auger screw*. An assembly drawing of the single screw feeder as illustrated in Figure 3-2 is presented in **Appendix C** with only

basic dimensions. Detailed drawings of the design were produced for manufacturing purposes and are available but have not been included for proprietary reasons.

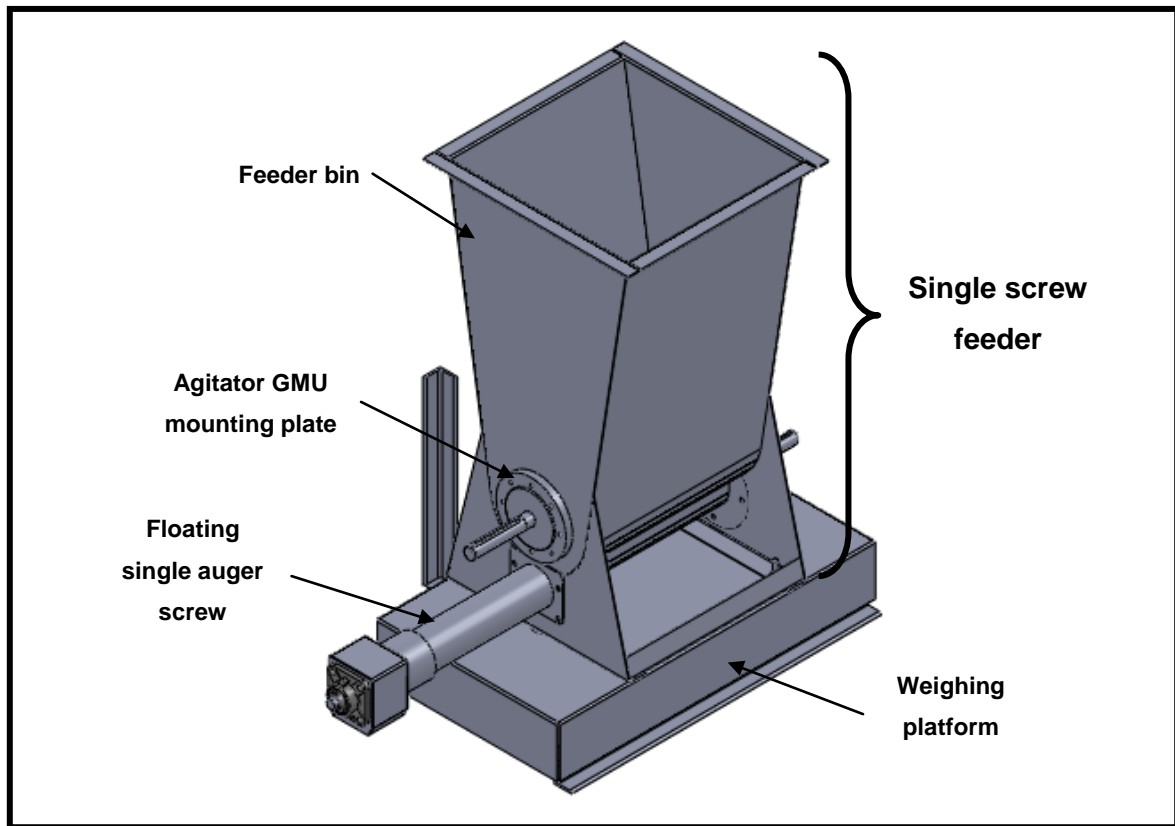


Figure 3-2: 3D Model of the single screw feeder of the test bench

To drive the floating single auger screw and the agitator shaft, they were coupled to Bauer geared motors. Details of the specifications of the geared motor units used are presented in Table 3-1.

Table 3-1: Geared motor unit specifications (Single screw feeder)

Application	Worm gear model	Motor kW @ 50Hz	Gearbox Ratio	Output (r/min)
Agitator	NMR 063	0.37	80:1	18
Feeder screw	NMR 063	0.75	25:1	56

### 3.3.2 Supply system

Figure 3-3 illustrates a 3D model of the developed supply system. The most important part of the supply system is the *bulk storage bin* designed to overcome bridging. The supply auger installed in the supply system is a standard of the shelf flexible screw conveyor supplied and

distributed by *Big Dutchman South Africa (Pty) Ltd.* The auger uses a centre-less spiral screw to convey the material.

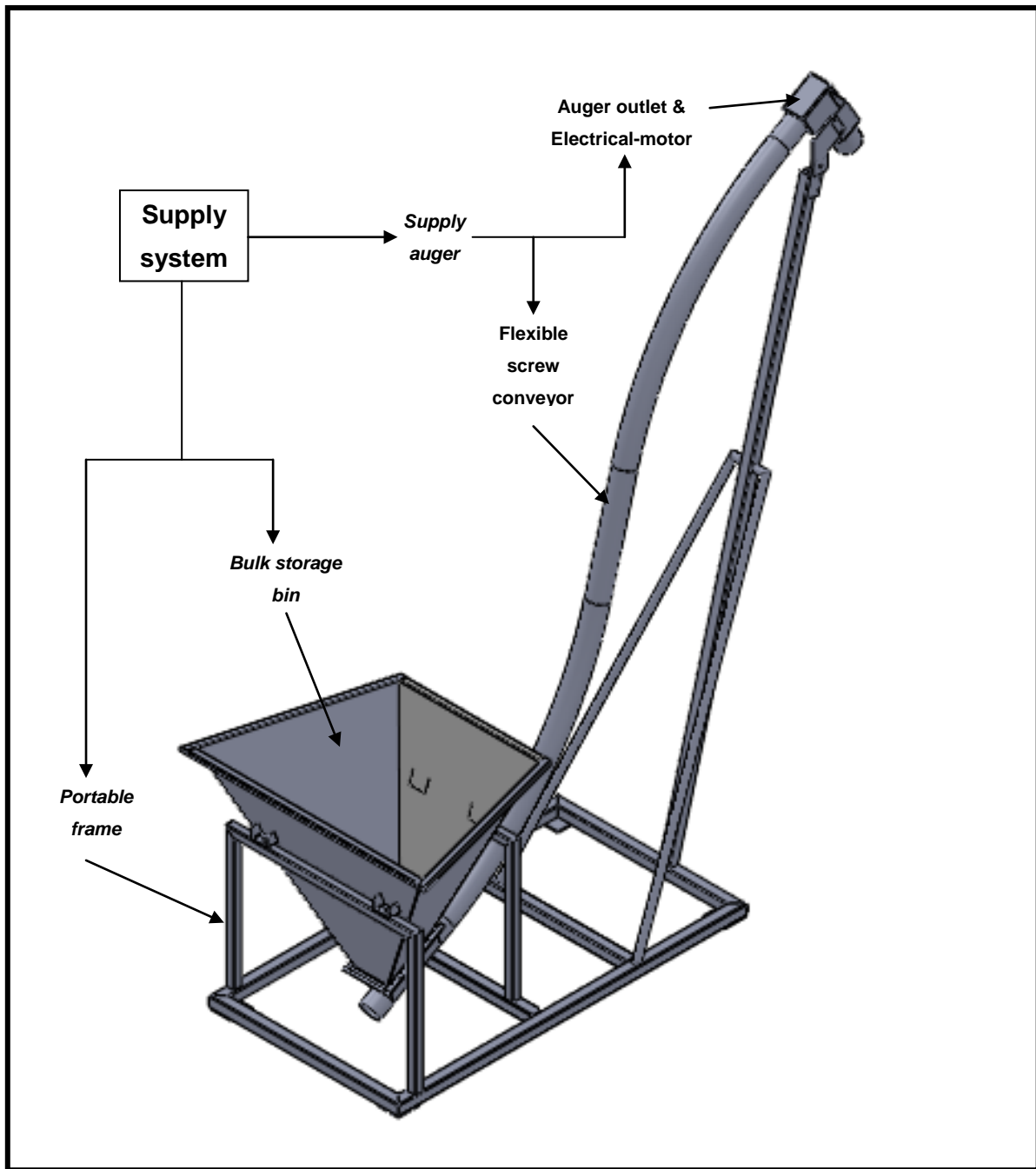


Figure 3-3: 3D Model of the supply system of the test bench

An assembly drawing of the supply system as illustrated in Figure 3-3 is presented in **Appendix C** with only basic dimensions. Detailed drawings of the design were produced for manufacturing purposes and are available but have not been included for proprietary reasons.

## 3.4 Control system hardware

### 3.4.1 Primary elements

Having reviewed the operating environment and conditions of weighing systems it was clear that the load cells to be selected needed to be corrosion resistant, moisture resistant and not be affected by dust or any other particles. The operating environment and conditions are not severe which allowed for the use of aluminium strain gauge load cells. The gross weight (maximum weight) of the single screw feeder was determined to be no more than  $\pm 200\text{kg}$ .

The load cell model selected for the weighing system was a *TEDEA Model 1042 single point load cell* with a 6 wire sense circuit. The six wire sense circuit has two additional sense wires which gives feedback on the excitation voltage reaching the load cells to the load cell instrumentation. Changes in lead resistance due to temperature change and/or cable excitation were overcome by feeding the voltage feedback into the appropriate instrumentation where the layout provides for compensation.

TEDEA Model 1042 load cells have a safe overload of 150% (% of rated capacity) and an ultimate overload of 300% (% of rated capacity). With the gross weight of the feeder being no more than  $\pm 200\text{kg}$  and the load cells having overload safety factors, three TEDEA Model 1042 single point load cells with a rated capacity of 75kg each with an accuracy grade "E" was selected for the weighing system. The weighing system was also supplied with a junction box designed and manufactured by LOADTECH (Pty) Ltd.

A LOADTECH Model 6004/LC LED load cell controller which comes standard with a 16-bit Digital to Analog (D/A) convertor and with load cell excitation integrated, was selected for the weighing system. In addition the Option 3008 [Galvanic isolated DC supply (10-30Vdc) power supply was selected.

### Weighing platform

Figure 3-4 illustrates a 3D model of the developed weighing platform for the weighing system. In an attempt to reduce the self imposed mechanical vibrations of the single screw feeder on the load cells, rubber mountings were installed. The single screw feeder mounts directly on the rubber mountings with only the load cell cover in between. The load cell cover as illustrated in Figure 3-4 does not support the weight of the feeder; it is only there for protection of the load cells and the junction box. The junction box is not illustrated in Figure 3-4, but it is also positioned under the load cell cover.

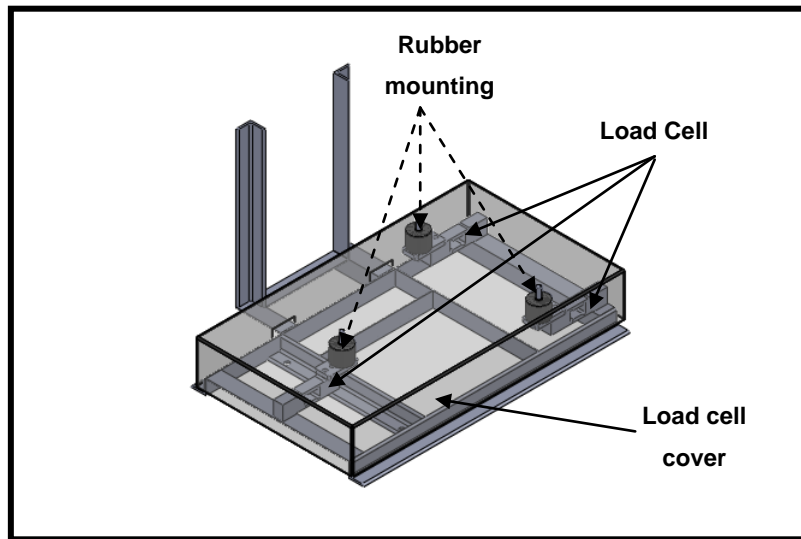


Figure 3-4: 3D Model of the weighing platform of the test bench

An assembly drawing of the weighing platform as illustrated in Figure 3-4 is presented in **Appendix C** with only basic dimensions. Detailed drawings of the design were produced for manufacturing purposes and are available but have not been included for proprietary reasons.

### 3.4.2 Controllers

The PLC selected for the control system was a, 1766-L32BWA AB *MicroLogix 1400 controller* with 15-bit ( $2^{15}$ ) internal resolution. Most modern automated industrial systems provide for digital- and analog signals. It was therefore very important to make sure that the selected controller had sufficient input and output interface options and that the correct signal types were provided for. The 1766-L32BWA controller does not come standard with embedded analog input and output interface options and therefore required I/O modules. The additional I/O modules which were added to the PLC for the control system are:

- Module 1: Model: 1762-IF4 → Allen-Bradley 4-Channel Analog Input module
- Module 2: Model: 1762-OF4 → Allen-Bradley 4-Channel Analog Output module.

The operator interface selected for the control system was a, 2711P-T10C4A1 AB PanelView Plus 1000 terminal.

### 3.4.3 Final control element

The selected VSD for the control system was a, 22B-D4P0N104 AB PowerFlex 40 3-phase AC drive. It has an environment rating of IP-20, which is sufficient for this specific control system as it was mounted inside the electrical enclosure (control panel).

### 3.4.4 Control panel

The PLC based control system was mounted and wired into a control panel housing as illustrated in Figure 3-5. Presented in **Appendix B**, is the complete Process and Instrumentation Diagram (P&ID) of the control panel.

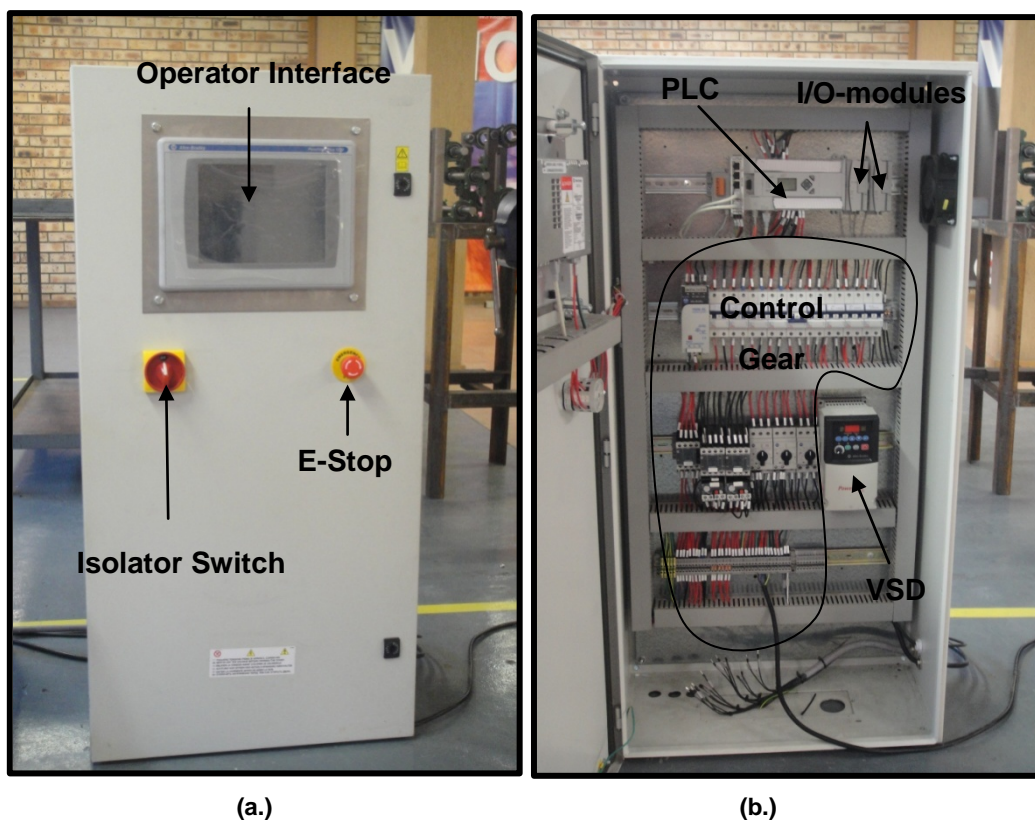


Figure 3-5: Control panel general arrangement: (a.) Showing the positioning of the operator interface, the isolator switch and the emergency stop (b.) Showing the PLC, I/O-modules, control gear and the VSD

The control panel was supplied with 3-phase power with distribution to all the components of the test bench via the control gear. An isolator switch and emergency stop (E-Stop) button was provided on the front of the control panel just below the operator interface. The isolator switch powered up the entire control panel; and the emergency stop button was installed to halt the entire gravimetric feeding system whenever the feeding process became unstable.

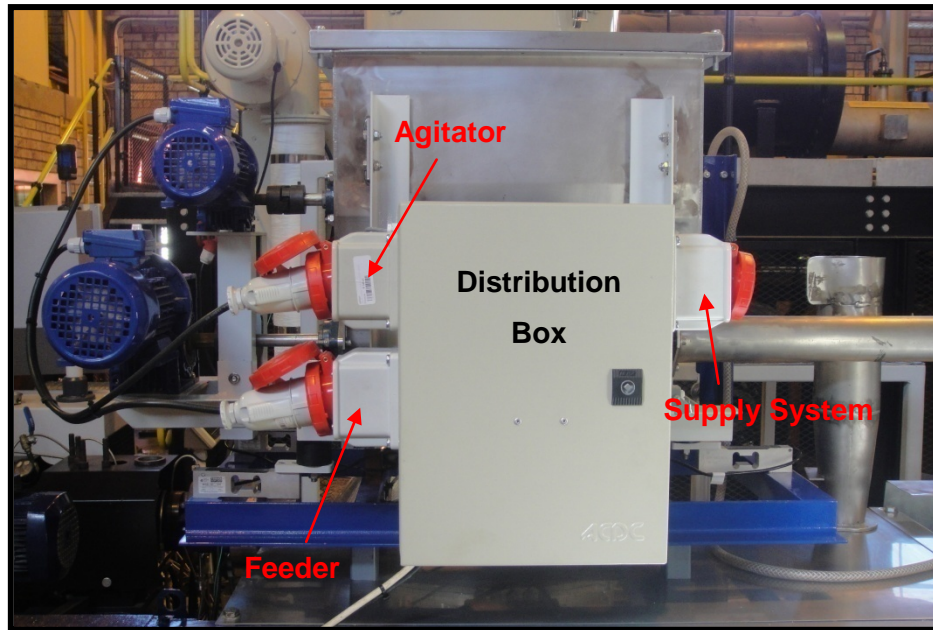


Figure 3-6: Photograph of the distribution box

Figure 3-6 illustrates the distribution box installed to simplify the wiring of the control system. The distribution box was connected to the control panel with a single multi-core cable. In the distribution box the multi-core cable was split to the feeder, agitator, supply system and the load cell controller which was situated inside the distribution box. The output of the load cell controller was a 4-20mA signal and therefore a dedicated single twisted pair overall screened cable was used for this specific signal between the load cell controller and the PLC.

### 3.5 Summary

Chapter 3 presents the design and component selection of the developed gravimetric feeding test bench. With the design of the test bench and the control system complete, it was possible to attend to the applicable *control system software*.

## Chapter 4: CONTROL SYSTEM SOFTWARE

Chapter 4 presents a detailed description of the control system software (user program) developed for the gravimetric feeding of a twin screw extruder. The user program is available but has not been included in the document for proprietary reasons.

### 4.1 User program

Figure 4-1 presents a schematic block diagram of how the *user program* was constructed using sub-programs (LADDERS) based on the devised control algorithms of which the most important are shown in **Appendix A**.

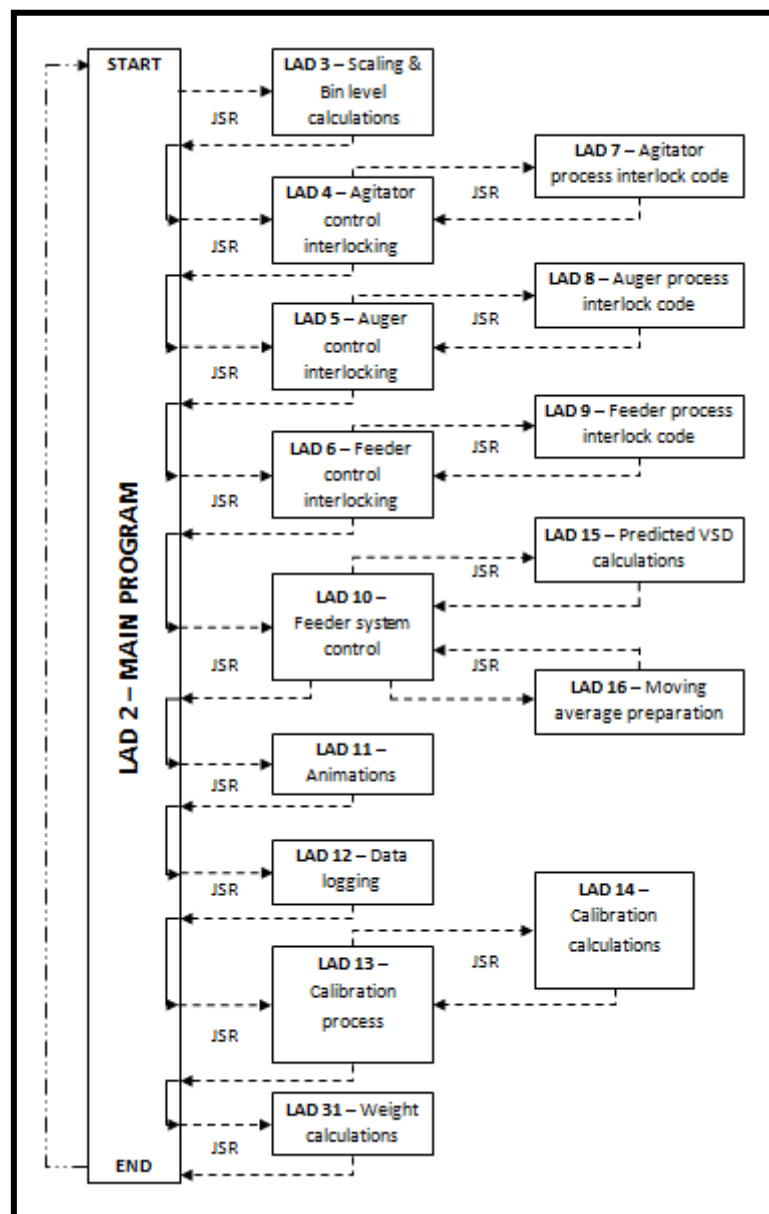


Figure 4-1: Schematic block diagram of the user program sub-routine scheme

Writing the *user program* in sub-programs simplified the design process, programming and fault finding. Jump to subroutine (JSR) instruction pallets were used to interlink the sub-programs. The *user program* was developed with RSLogix 500 as the selected control system utilizes an AB MicroLogix 1400 PLC. *PI-control* was selected as the most suitable method of control by way of selection that was based on the scheme as presented in Figure 2-14 (p. 25).

The *main program (LAD 2)* in Figure 4-1 is the first of the sub-programs in the *user program* and is labelled as the master sub-program. It has a few basic control functions to execute with initial start-up, but its main function is to control the first row of sub-programs which forms the main structure of the user program. As some of the control signals are not in the correct format, they need to be scaled (converted) as required by the user program which is handled in sub-program *LAD 3*. The main signals which are scaled are:

- Screw feeder drive speed reference output:<sup>1</sup>
  - 0 – 16383 → 6240 – 31200
- Feeder VSD frequency reference feedback:<sup>2</sup>
  - 6240 – 31200 → 0 – 16383
- VSD frequency in Hz:<sup>3</sup>
  - 0 – 16383 → 0 – 50Hz
- Feeder bin weight in kilogram (kg):<sup>4</sup>
  - 6240 – 31200 → 0 – 60kg

Once *LAD 3* has completed the scaling instructions it then goes on to calculate the *bin high level (BHL)*, *bin low level (BLL)*, *calibration high level (CHL)* and the *calibration low level (CLL)* in kilogram, from the percentage values [0% (0kg)-100% (60kg)] as entered via the graphical user interface (GUI).

---

<sup>1</sup> The fixed screw speed as entered via the operator interface is scaled from a 14-bit value to a 15-bit analog output (4-20mA) value as required by the user program and the VSD.

<sup>2</sup> The VSD output (4-20mA) is fed back to the user program and scaled from a 15-bit value to a 14-bit value as it is required by the control system.

<sup>3</sup> The VSD frequency is scaled from a 14-bit value to a frequency (Hz) value for visual display on the operator interface.

<sup>4</sup> The analog input (4-20mA) from the weighing system is scaled from a 15-bit value to the calibrated (0-60kg) bin weight value.

Sub-programs *LAD 4* and *LAD 7* linked together with a JSR instruction pallet, contain the required ladder logic code to control the stop and start of the agitator's electrical motor, for both the manual- and automatic operating modes. If certain conditions are true or false then a series of bits are set or cleared in the user-program which allows for *LAD 4* and *LAD 7* to either start or stop the agitator. The start and stop control of the supply auger- and the feeder motor is done in a similar manner as described above, it's only the conditions which varies for each system.

The GUI allows for complete control of all the different systems in the test bench for both the manual- and automatic operating modes as required by the design specifications. The GUI makes use of an animation to illustrate when the agitator is running this is handled by sub-program *LAD 11*. To completely evaluate the control system and the control system software required experimental data and sub-program *LAD 12* allows just that. *LAD 12* moves the variables to be logged every five hundred milliseconds (500ms) to a specific variable location in the PLC CPU's memory, from where *data capturing software* is used to repeatedly log the required data.

Sub-program *LAD 31* applies signal conditioning to the weight signal ( $m_B$ ) to eliminate most of the imposed noise on the weighing system through two moving averages. Figure 4-2 presents a schematic block diagram of the weighing system signal processing process code. The first moving average (MA) filters the raw weight signal ( $m_B$ ) as received from the weighing system and the result of this MA is referred to as the actual weight ( $m_{B,MA}$ ). The second MA filters the loss-in-weight subtraction ( $\Delta m_B$ ) and the result of this MA is the *actual weight loss* ( $\Delta m_{B,MA}$ ) which is the desired result of the signal processing process. The *actual weight loss* is mainly used by the *gravimetric weighing cycle* as its PV but it is also used to calculate the instantaneous feed rate ( $\dot{m}_l$ ) in *kg/h* during all fixed screw speed operations, as illustrated in Figure 4-2.

The sub-programs illustrated by Figure 4-1 are used in different ways by the *user program* for the manual- and automatic operating modes. Selection between manual- and automatic operation is provided for on the GUI. When the feeding system is operated in manual mode it is basically the same as an open-loop control system. It does not make use of any feedback control to adjust the feeder screw speed in any way, thus gravimetric feeding is not achieved. This means that the feeding system can only feed volumetrically.

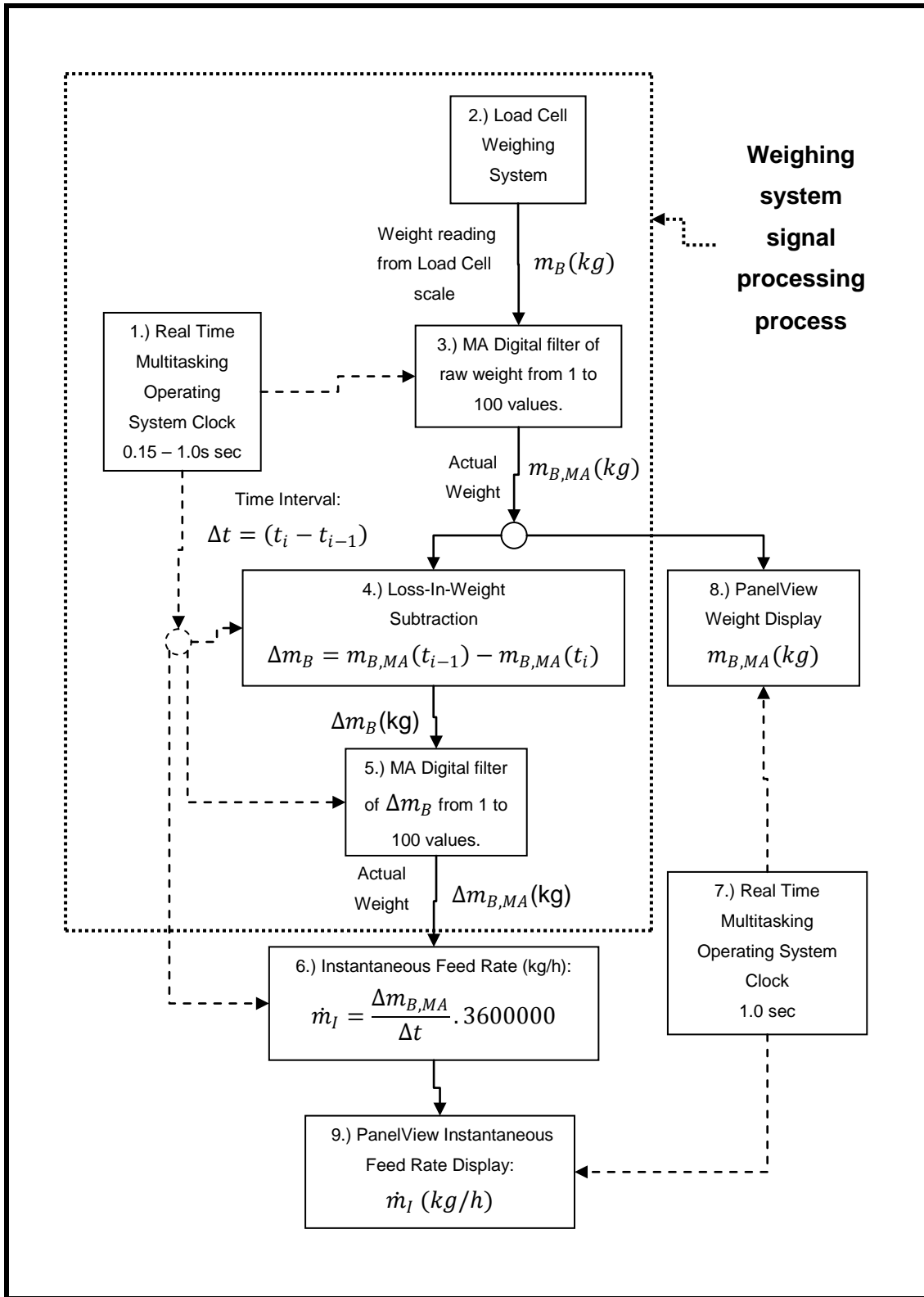


Figure 4-2: Schematic block diagram of the weighing system signal processing process code

Volumetric feeding means that the feeder is running at a fixed screw speed (FSS) which is entered via the operator interface as a percentage value. The frequency (Hz) range of three phase induction electrical motors is normally 0Hz (0%) to 50Hz (100%), depending on the make and type of the electrical motors. The operator therefore has the ability to run the feeder at anything from 0Hz (0%) to 50Hz (100%) fixed screw speed. At 100% FSS the feeder should deliver a volumetric feed rate equal the designed maximum of  $\pm 300\text{kg/h}$ . For the remainder of this document and study, the volumetric feed rate will be referred to as the *instantaneous feed rate*.

When the feeding system is operated in auto mode and it is in the *feeding cycle*, the control system and the user program then functions as a SISO closed loop feedback system. It compares the PV (actual weight loss) with the SP (desired weight loss entered via the operator interface) to generate an error. The error conditioned by the controller and tuning, drives the appropriate changes in the FCE (variable speed drive) such that the PV is driven back to the SP. For the remainder of this document and study, this is referred to as the *gravimetric weighing cycle*. Figure 4-3 presents a schematic block diagram of the developed *gravimetric weighing cycle code* of which segments 4, 5, 16, 17 and 18 are programmed in sub-program LAD 2, segments 7 and 13 are programmed in sub-program LAD 3, segments 2, 3, 6, 11 and 12 are programmed in sub-program LAD 10 and segments 1, 8, 9, 10 and 15 in sub-program LAD 31.

To overcome the problem of material bulk density variations in gravimetric feeding during the *refilling cycle*, a *calibration process/algorithm* was developed and implemented in the user program to obtain the volumetric (fixed screw speed) characteristics of the material being fed. The volumetric characteristics of the material being fed are then used by the user program to regularly adjust the volumetric feed rate (fixed screw speed) during the *refilling cycle* (as a function of the level of material as weighed in the bin), as the *weighing system signal processing process* (Figure 4-2 OR segments 1, 8, 9, 10 and 15 in Figure 4-3) is rendered blind during refilling. The volumetric characteristics are also used in an attempt to shorten the response period of the installed PI-controller. Therefore all materials being fed with the same feeder, require *calibration* to obtain their *calibration constants* and *volumetric characteristics* prior to automatic feed.

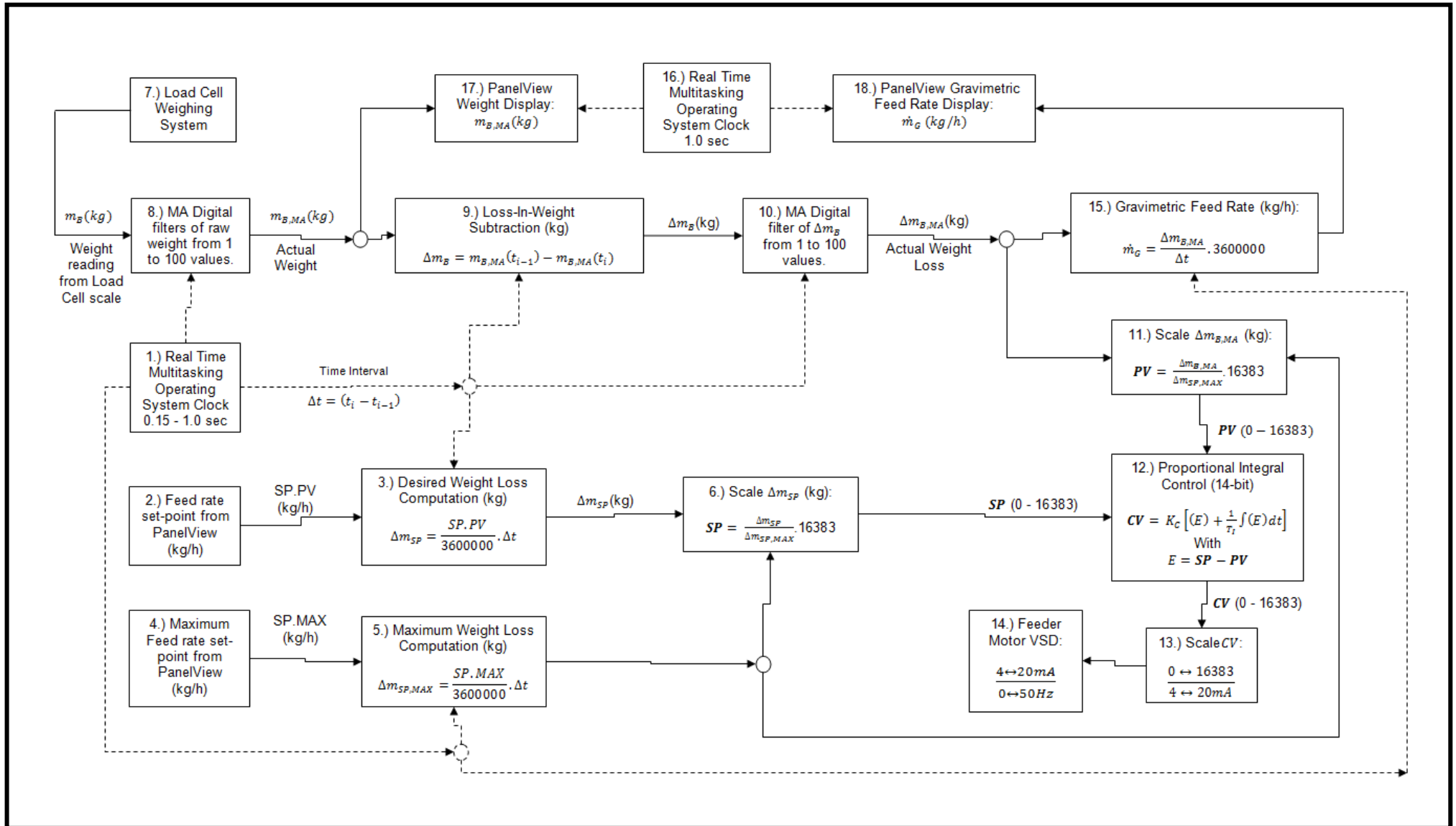


Figure 4-3: Schematic block diagram of the gravimetric weighing cycle code

## 4.2 Calibration

Extensive experimental testing of feeders which are supplied with an agitator and which are affected by material bulk density variations revealed that there is a relatively linear decrease in the feed rate up the agitator from where the decrease in feed rate then changes. Figure 4-4 presents a graphical plot of such a decreasing *feed rate (kg/h)* curve against *feeder bin weight (kg)* during a typical *feeding cycle*.

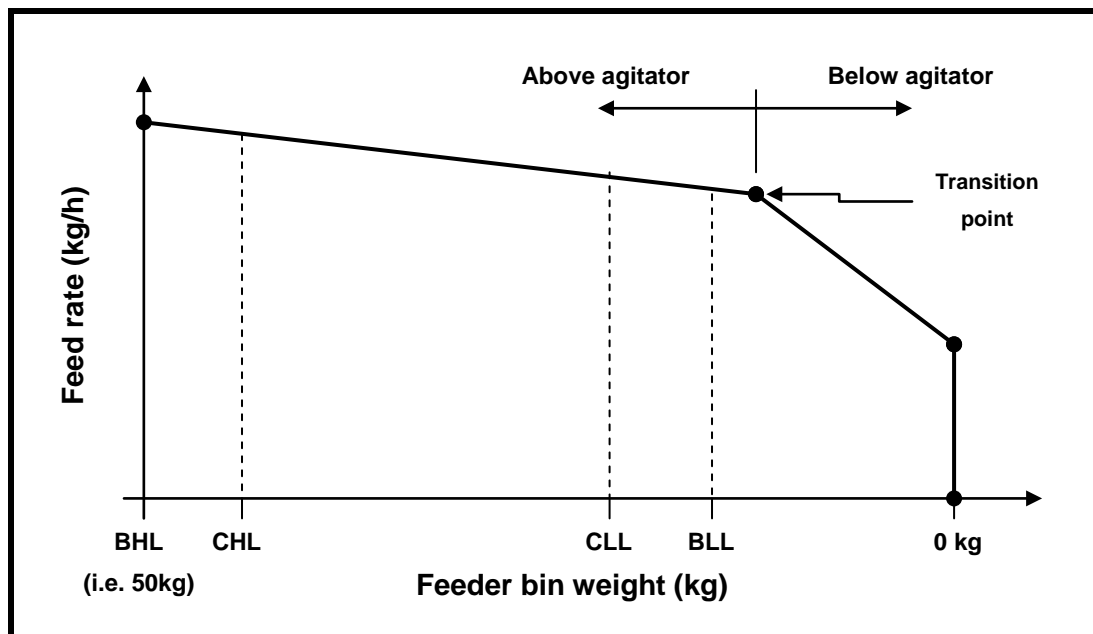


Figure 4-4: Decreasing feed rate of a feeder which is supplied with an agitator and which is affected by material bulk density variations during a typical feeding cycle

Due to the complexity of the programming and the relatively linear trend of the decreasing feed rate it was decided to make use of only two calibration points (bin levels) for the devised calibration process, which are referred to as the *calibration high level (CHL)* and the *calibration low level (CLL)*. Both of these bin levels are entered via the operator interface as a percentage value of the weighing systems calibrated kilogram range [i.e. 0% (0kg)-100% (60kg)]. Referring to Figure 4-4, it is clear that the *CLL* and the *bin low level (BLL)* must be set above the *transition point* to ensure the accuracy of the *calibration constants*. The *transition point* is defined through extensive experimental testing and will vary from feeder to feeder.

**Appendix A.1** presents a schematic block diagram of the developed *calibration process/algorithm (CP)*, which can be activated via the GUI as required and is programmed in sub-program *LAD 13*. The CP code acquires volumetric data of the material being fed at



- $\Delta m_{B,CHL(50\%)} = \sum_{i=1}^3 \Delta m_{B,CHL(50\%),i} / 3 \quad (kg) \quad (4.3)$

- $\Delta m_{B,CLL(50\%)} = \sum_{i=1}^3 \Delta m_{B,CLL(50\%),i} / 3 \quad (kg) \quad (4.4)$

- $m_{B,CHL} = \sum_{i=1}^6 m_{B,CHL,i} / 6 \quad (kg) \quad (4.5)$

- $m_{B,CLL} = \sum_{i=1}^6 m_{B,CLL,i} / 6 \quad (kg) \quad (4.6)$

Figure 4-5 is a graphical plot of typical calibration constants (4.1) - (4.4), as calculated by the CP code.

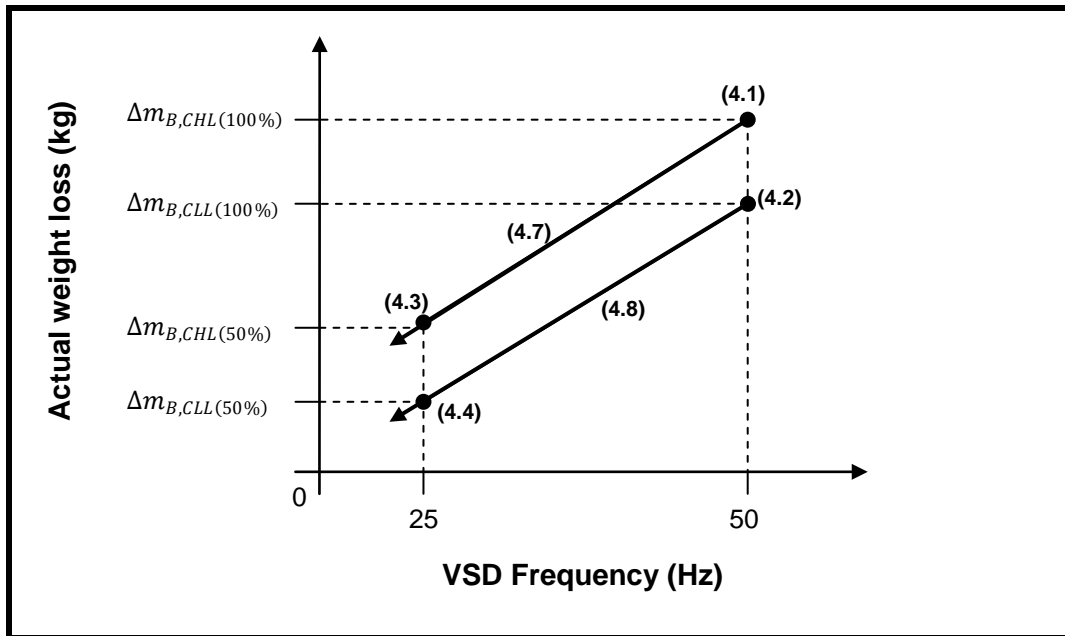


Figure 4-5: Graphical plot of typical calibration constants

The final results of the calibration calculations as programmed in *LAD 14*, are the equations of the linear trend lines (4.7) and (4.8) as shown in Figure 4-5. The equations are calculated by the CC code as illustrated below:

$$y_{CHL} = m_{CHL} \cdot x_{CHL} + c_{CHL} \quad (kg) \quad (4.7)$$

with

$$m_{CHL} = \frac{\Delta m_{B,CHL(100\%)} - \Delta m_{B,CHL(50\%)}}{25} \quad (kg/Hz) \quad (4.7.1)$$

$$c_{CHL} = \Delta m_{B,CHL(100\%)} - 2(\Delta m_{B,CHL(100\%)} - \Delta m_{B,CHL(50\%)}) \quad (4.7.2)$$

and

$$y_{CLL} = m_{CLL} \cdot x_{CLL} + c_{CLL} \quad (\text{kg}) \quad (4.8)$$

with

$$m_{CLL} = \frac{\Delta m_{B,CLL(100\%)} - \Delta m_{B,CLL(50\%)}}{25} \quad (\text{kg/Hz}) \quad (4.8.1)$$

$$c_{CLL} = \Delta m_{B,CLL(100\%)} - 2(\Delta m_{B,CLL(100\%)} - \Delta m_{B,CLL(50\%)}) \quad (4.8.2)$$

Referring to Figure 4-5, (4.7) and (4.8) is the linear relation approximation between the *actual weight loss* and the *VSD frequency* for two constant feeder bin weights [(4.5) and (4.6)] of a specific material, which are referred to as the *volumetric characteristics*. Therefore if the material type being fed is changed then the CP has to be recalibrated to obtain the calibration constants of the new material.

#### 4.2.2 Predicted VSD calculations / Predicted weighing cycle

The purpose of the *predicted VSD calculations code* which is programmed in sub-program *LAD 15* is to predict the *VSD frequency* for a given *SP* and *feeder bin weight*, from the *volumetric characteristics* of the material being fed as calculated by the CC code. Before the code in *LAD 15* is used to predict the *VSD frequency*, it first calculates the *predicted frequency constants* as follows:

Firstly, *LAD 15* uses (4.7) and calculates the first predicted frequency constant ( $x_{SP(CHL)}$ ) as,

$$x_{SP(CHL)} = \frac{SP - c_{CHL}}{m_{CHL}} \quad (\text{Hz}) \quad (4.9)$$

which is the predicted *VSD frequency*, for the given *SP* at the *CHL*. *LAD 15* then goes on to calculate the second predicted frequency ( $x_{SP(CLL)}$ ) by making use of (4.8) as,

$$x_{SP(CLL)} = \frac{SP - c_{CLL}}{m_{CLL}} \quad (\text{Hz}) \quad (4.10)$$

which is the predicted *VSD frequency*, for the given *SP* at the *CLL*. Figure 4-6 is a graphical plot of typical *predicted frequency constants* (4.9) and (4.10), as calculated by the code in sub-program *LAD 15*. The final result of the calculations in the code of *LAD 15* is the equation of the linear trend line (4.11) as shown in Figure 4-6. The equation as calculated by the code in *LAD 15* is:

$$y_{SP} = m_{SP} \cdot x_{SP} + c_{SP} \quad (\text{kg}) \quad (4.11)$$

with

$$m_{SP} = \frac{m_{B,CHL} - m_{B,CLL}}{x_{SP(CHL)} - x_{SP(PLL)}} \quad (\text{kg} / \text{Hz}) \quad (4.11.1)$$

$$c_{SP} = m_{B,CHL} - m_{SP} \cdot x_{SP(CHL)} \quad (\text{kg}) \quad (4.11.2)$$

Equation (4.11) gives the linear relationship between the feeder bin weight ( $m_B$ ) and the VSD frequency for a given feed rate set point (SP), to maintain a constant feed rate equal to the SP according to the volumetric characteristic of the material being fed; which is referred to as the *predicted frequency curve*.

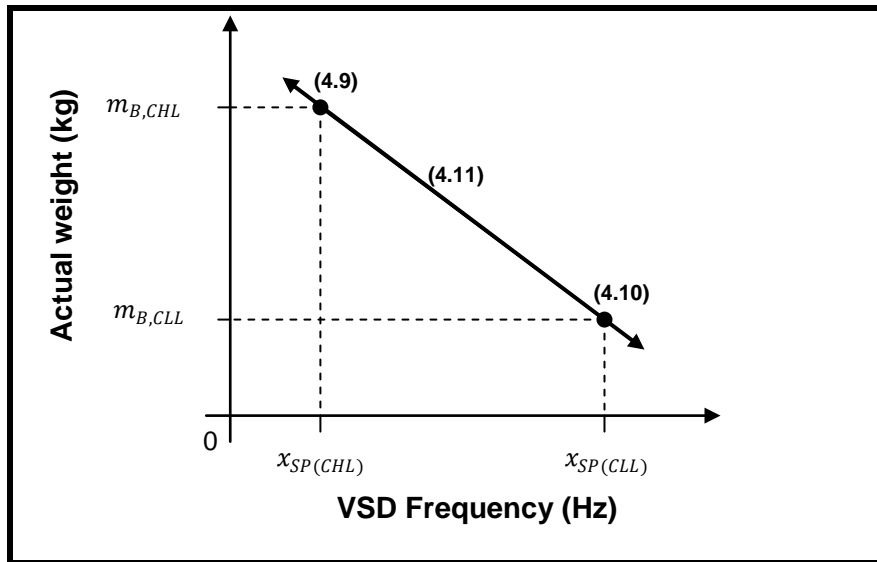


Figure 4-6: Graphical plot of typical predicted frequency constants

With the relationship between the SP, feeder bin weight and VSD frequency established, the required *predicted VSD frequency* ( $x_{SP(m_B)}$ ) is calculated from (4.11) as,

$$x_{SP(m_B)} = (m_B - c_{SP}) / m_{SP} \quad (\text{Hz}) \quad (4.12)$$

which is the predicted VSD frequency for a feed rate equal to the SP at the current feeder bin weight ( $m_B$ ). This then serves as a starting point for the *gravimetric weighing cycle* and as the *predicted weighing cycle* for the *refilling cycle*. Every time the SP is changed the code in sub-program LAD 15 recalculates (4.12).

### 4.3 Feeder system control

Sub-program *LAD 10* (feeder system control) can be seen as the most important sub-program of the user program, as it contains all the devised *gravimetric control algorithm codes* and most of the *gravimetric weighing cycle's code*. The developed *gravimetric control algorithms* are composed of:

- PI-control algorithm (**Appendix A.2**)<sup>5</sup>
- Assisted PI-control algorithm (**Appendix A.3**)<sup>6</sup>
- Changed feed rate algorithms (Feeding- & Refilling cycle) (**Appendix A.4**)<sup>7</sup>

Different from the *assisted PI-control algorithm*, the *PI-control algorithm* only makes use of the *gravimetric weighing cycle* during the *feeding cycle*. This was done to be able to illustrate the effects (positive and/or negative) of combining the *predicted weighing cycle* and the *volumetric characteristics* into a single control algorithm during a feeding cycle.

The *gravimetric control algorithms* require that the moving averages of the *weighing system signal processing process* is prepared in a certain way for the start of the *gravimetric weighing cycle* and sub-program *LAD 16* allows just that. As illustrated in Figure 4-1, *LAD 10* is linked to *LAD 15* and *LAD 16* through *jump to subroutine (JSR)* instruction pallets, to complete the automatic operating mode.

### 4.4 Summary

Chapter 4 presents the discussion of the structure of the *user program code* that was developed for the control system. The control system hardware, software and the feeding system were interfaced into a fully functional gravimetric feeding test bench.

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<sup>5</sup> This is the control algorithm for the code when only the *gravimetric weighing cycle* is used by the code during the feeding cycle.

<sup>6</sup> This is the control algorithm for the code when both the *gravimetric weighing cycle* and the *predicted VSD calculations* are used by the code during the feeding cycle.

<sup>7</sup> These are the control algorithms of the code when a feed rate change occurs for both PI-control and assisted PI-control during a *feeding-* or a *refilling cycle*.

## Chapter 5: ALGORITHM VERIFICATION

Chapter 5 presents a detailed discussion of the experimental verification of the developed *gravimetric control algorithms* and the *gravimetric weighing cycle*.

### 5.1 Experimental set-up

#### 5.1.1 Feeding system set-up

Figure 5-1 presents a photograph of the experimental set-up of the developed feeding system (single screw feeder & supply system) with the feeder mounted on the weighing platform. The *control panel* is not shown in Figure 5-1 as it has been discussed and illustrated in Chapter 3.4.4.

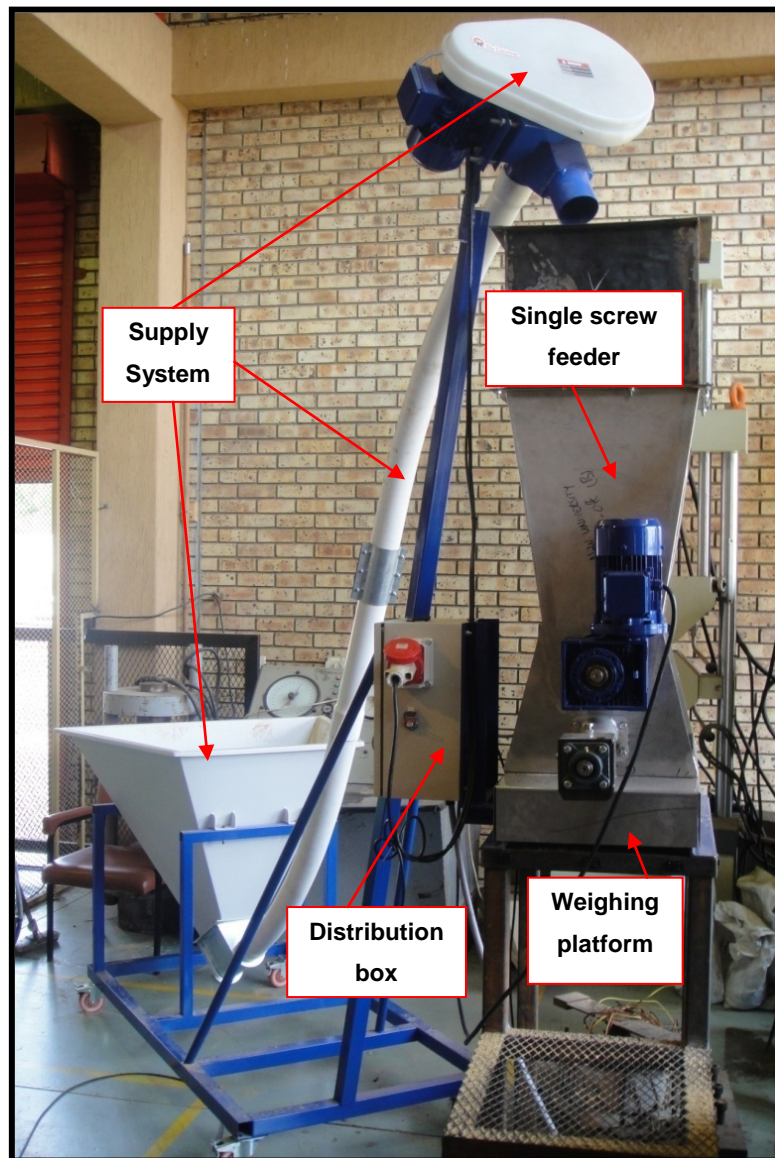


Figure 5-1: Photograph of the feeding system as assembled

The material used by the feeding system for the experimental verification process was a premixed material (i.e. dog food premix) with a material bulk density of approximately  $650\text{ kg/m}^3$ .

## 5.2 Experimental procedure

Initial experimental testing of the test bench revealed that excessive mechanical vibrations were being transferred to the weighing system from the single screw feeder. This influenced the *weighing signal processing process* negatively. The MA-time (weight signal sampling time for the MA's) had to be increased from a desired minimum value of 150ms to 500ms and the MA-length (amount of accumulated values in the MA's) to a minimum of 30 increments.

Presented in Table 5-1, is the control system software set-up via the GUI as used for the algorithm verifications, which is dependent on the material used. The PI-controller set-up ( $K_c, T_i$  and  $LUT$ ) was obtained through prior extensive experimental testing.

**Table 5-1: GUI software set-up**

Nr.	Variable	Value	Units
1	Bin High Level (BHL)	92 <sup>8</sup>	%
2	Bin Low Level (BLL)	33	%
3	$K_c$ (Controller Gain)	0.4	-
4	$T_i$ (Reset Term)	0.1	Minutes/Repeat
5	$LUT$ (Loop Update Time)	1	s
6	MA-time	0.50	s
7	MA-length	30	-
8	CHL	75	%
9	CLL	15	%
10	Max Feed Rate	300	kg/h

Before any experimental verification of the gravimetric control algorithms could be conducted, the material which was used had to be *calibrated*. A single experimental feeding process was then developed for the evaluation of the *PI-control algorithm code* and the *assisted PI-control algorithm code*. Table 5-2 illustrates the developed experimental feeding process actions. It also illustrates a feed rate change during the first *feeding cycle* and the

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<sup>8</sup> All *bin levels* are entered as a percentage value (0 - 100%) of the weighing systems calibrated kilogram range (0 - 60kg)

refilling cycle of the experimental process. This was done to incorporate the *changed feed rate algorithm code* of both the *PI-control* and the *assisted PI-control*.

**Table 5-2: Table of procedure and steps to generate PI- and assisted PI-control experimental data**

	Step no.	Operational Action		Bin weight	
		Description	Feed rate (kg/h)	%	kg
<b>Feeding Cycle 1</b>	1	Start feeder	250	90	54
	2	Change feed rate	150	66	40
<b>Refilling Cycle</b>	3	Change feed rate	250	66	40
<b>Feeding Cycle 2</b>	4	Stop feeder	0	66	40

The variables that were acquired by the data capturing software (Modbus RTU software package) during all experimental tests was the *bin weight (kg)*, *set point (kg/h)*, *gravimetric feed rate (kg/h)* and the *VSD frequency (Hz)*. Table 5-3 presents a list of the variables with the sampling rate of each variable.

**Table 5-3: Experimental variables & MODBUS RTU sampling rate**

Variable no.	Measurement	Unit	MODBUS RTU Sampling Rate
1	Bin weight	kg	1-second intervals
2	Set point	kg/h	1-second intervals
3	Gravimetric feed rate	kg/h	1-second intervals
4	VSD Frequency	Hz	1-second intervals

The data acquired by the data capturing software was processed and converted into graphical plots of the results to characterize the developed gravimetric control algorithms.

## 5.3 Experimental results

### 5.3.1 Calibration results

Table 5-4 illustrates the results obtained by the calibration process (CP) code and the calibration calculation (CC) in order to characterize the material used. According to (4.7), (4.8) and Table 5-4 the equations of the characterization high level (5.1) and the characterization low level (5.2) were found to be:

$$y_{CHL} = 2.604e^{-06} \cdot x_{CHL} + 0.00184 \quad (kg) \quad (5.1)$$

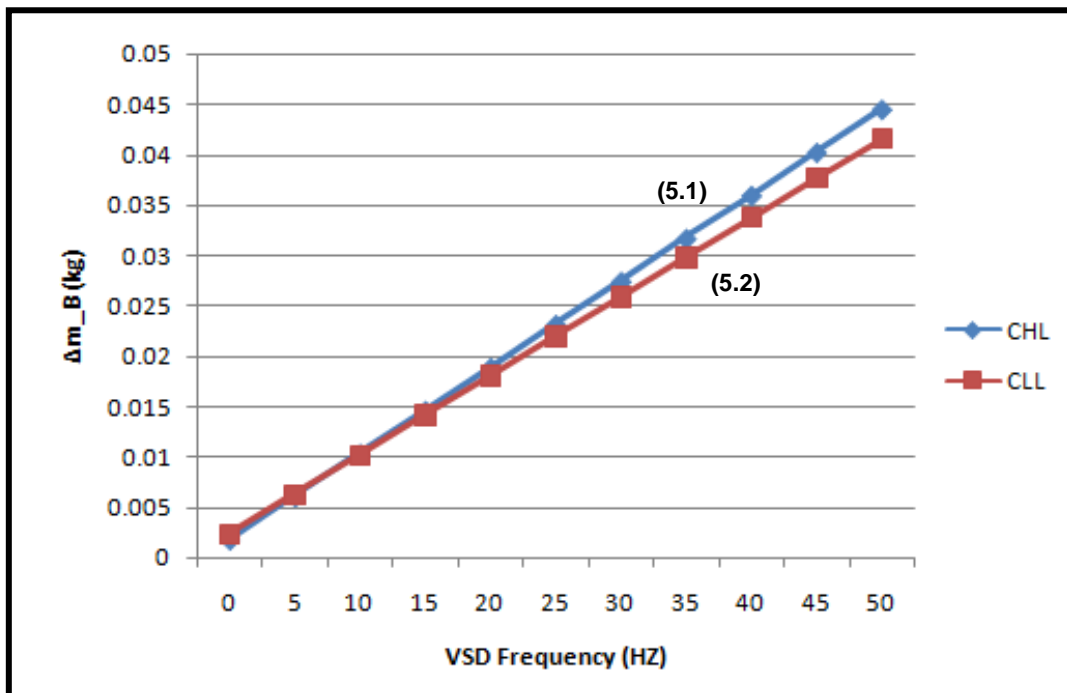
and

$$y_{CLL} = 2.388e^{-06} \cdot x_{CLL} + 0.00241 \quad (\text{kg}) \quad (5.2)$$

Figure 5-2, is therefore a graphical plot of the linear relation approximation between the *actual weight loss* against the *VSD frequency* for two constant feeder bin weights ( $m_{B,CHL}$  &  $m_{B,CLL}$ ) of the dog food premix obtained through (5.1) and (5.2), which are referred to as the *volumetric characteristics*.

**Table 5-4: CP- and CC Results**

Nr.	Variable	Eq.	Value	Units
1	$m_{B,CHL}$	(4.5)	44.99	kg
2	$m_{B,CLL}$	(4.6)	8.99	kg
3	$\Delta m_{B,CHL(100\%)}$	(4.1)	0.044493	kg
4	$\Delta m_{B,CLL(100\%)}$	(4.2)	0.041457	kg
5	$\Delta m_{B,CHL(50\%)}$	(4.3)	0.023167	kg
6	$\Delta m_{B,CLL(50\%)}$	(4.4)	0.021899	kg
7	$m_{CHL}$	(4.7.1)	2.604e-06	kg/Hz
8	$c_{CHL}$	(4.7.2)	0.00184	-
9	$m_{CLL}$	(4.8.1)	2.388e-06	kg/Hz
10	$c_{CLL}$	(4.8.2)	0.00241	-



**Figure 5-2: Graphical plot of the calibrated volumetric characteristics**

To illustrate the accuracy/inaccuracy of the volumetric characteristics a test was done with the *predicted weighing cycle*. The *assisted PI-control algorithm code* (Appendix A.6) was altered, so that it remained at “Step 11” (predicted weighing cycle) for a single feeding cycle. The desired feed rate (SP) for the verification of the volumetric characteristics was selected to be 275kg/h ( $\Delta m_B = 0.03819\text{kg}$ ). The equation of the *predicted frequency curve* for the desired set point of 275kg/h was calculated by the code in LAD 15 as,

$$m_B = -0.03166 \cdot x_{SP(m_B)} + 486.99 \quad (\text{kg}) \quad (5.3)$$

With the relationship between the *SP*, *feeder bin weight* and *VSD frequency* established, the required *predicted VSD frequency* was calculated by the code from (5.3) as,

$$x_{SP(m_B)} = \frac{m_B - 486.99}{-0.03166} \quad (\text{Hz}) \quad (5.4)$$

which is the *predicted VSD frequency* for a feed rate equal to 275kg/h at any feeder bin weight ( $m_B$ ), ranging from 0kg to 60kg as that was the calibrated range of the weighing system. Figure 5.3 presents a graphical plot of the data obtained by the Modbus RTU software during the experimental test.

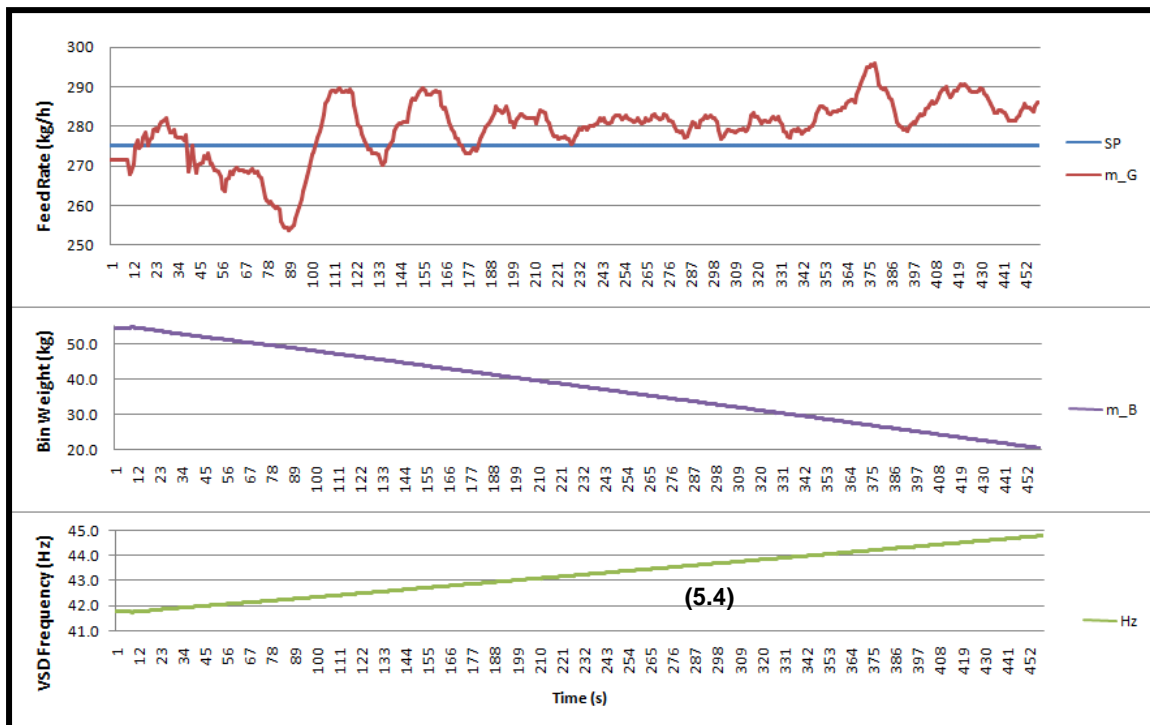


Figure 5-3: Graphical plot of the predicted weighing cycle experimental test

The top section of Figure 5-3 represents the *set point* (blue line) and the *feed rate* (red line) as calculated by the code during the *predicted weighing cycle* test, against time. It is clear that there is a difference between the SP value and the calculated feed rate. This occurred because of the CLL and the BLL that was selected below the transition point of the feeder, which lead to the *calibration constants* being inaccurate. The middle section of Figure 5-3 represents the decreasing bin weight against time. The most important section of Figure 5-3 is the bottom section, which is a graphical plot of (5.4). It illustrates that the *predicted weighing cycle code* increased the *VSD frequency* as the *bin weight* decreased according to the *volumetric characteristics* of the material being fed.

### 5.3.2 PI-control

Figure 5-4 presents a graphic plot of the results generated by the *PI-control algorithm code* with the experimental feeding process (Table 5-2). Referring to (2.1) the initial *percentage overshoot* was calculated to be  $\pm 28\%$  and reading of Figure 5-4 the *initial settling time* (time to settle to within 2% of the desired value) of the control system was approximately 2 minutes.

Illustrated at the top of Figure 5-4, is the *set point* (kg/h [blue]) and the *gravimetric feed rate* (kg/h) [red] against time which illustrates the desired feedback control which is also the desired result of the entire research project. The middle section of Figure 5-4 illustrates the *bin weight* [purple] against time. This is included in the graphical illustration of the results for one reason only, to differentiate between the *feeding cycles* and the *refilling cycles*. The bottom section of Figure 5-4 represents the *VSD frequency* (Hz) [green] as received from the PI-controller against time. The change in *VSD frequency* actually represents the true change in the *gravimetric feed rate*. The response of the *gravimetric feed rate* as illustrated by Figure 5-4 lags behind the varying VSD frequency with a time which is directly proportional to the length (time) of the moving averages in the weighing system signal processing.

A very important section of Figure 5-4 is the refilling cycle. This section illustrates that the *predicted weighing cycle code* decreased the VSD frequency according to the volumetric characteristics and it also allowed for a feed rate change which is not achievable by conventional control systems. The main goal of this specific experimental test was not to measure the performance and response of the control system against any of the design specifications; but to generate a baseline against which the *assisted PI-control code* could be compared.

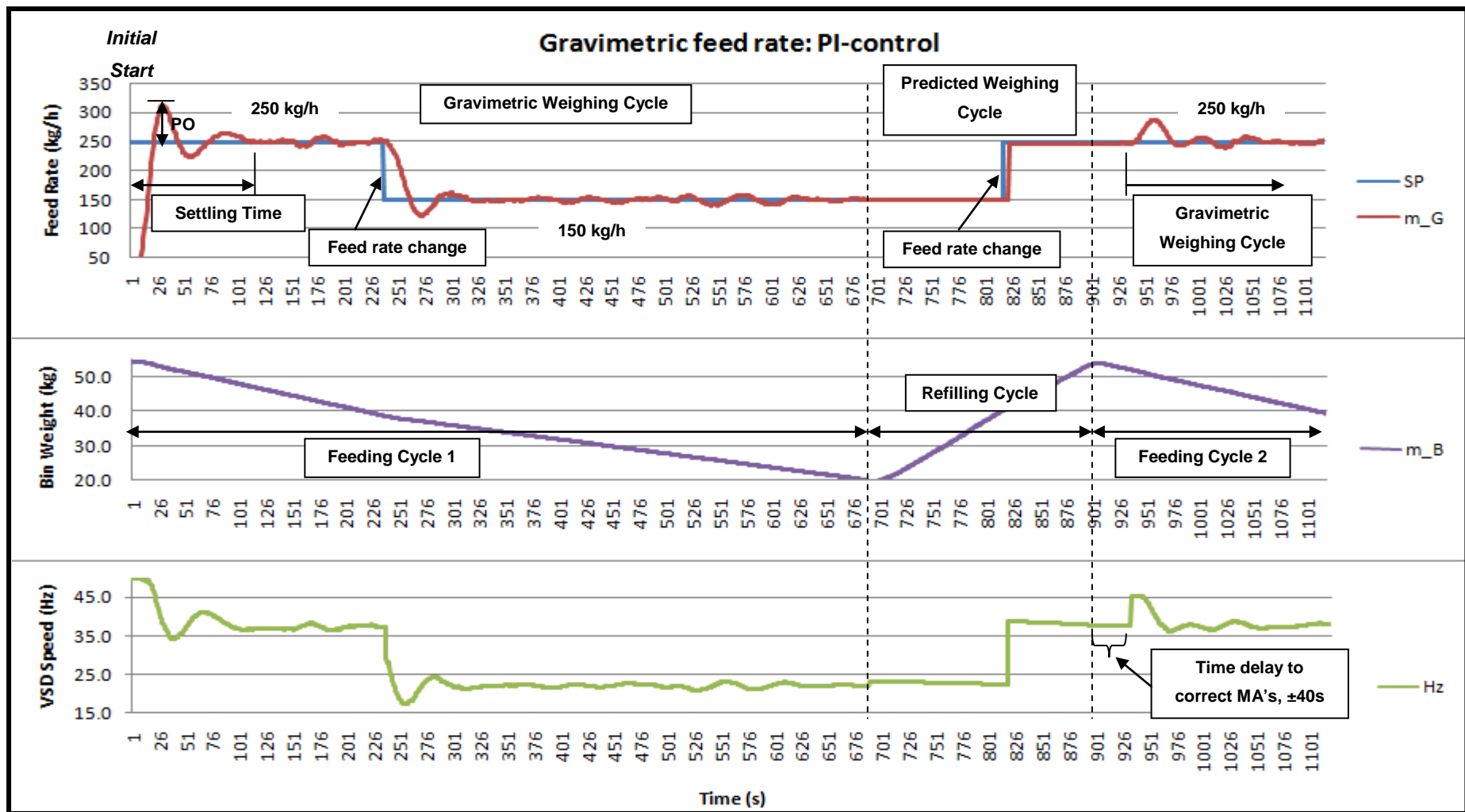


Figure 5-4: Graphical plot of the experimental results generated by the PI-control code

### **5.3.3 Assisted PI-control**

Figure 5-5 presents a graphic plot of the results generated by the *assisted PI-control algorithm code* with the experimental feeding process (Table 5-2). The most important illustration of Figure 5-5 is the illustration of a relatively smooth transition between the *predicted weighing cycle (PWC)* and the *gravimetric weighing cycle (GWC)* at the “Initial Start” of the feeding process and the second feeding cycle.

As the PI-controller was in AUTO at all times, extensive experimental testing revealed that a smooth transition was achieved; when at the moment of transition the CV (PI-controller output) matched the frequency (Hz) of the *predicted weighing cycle*. This was however not always the case, as illustrated by the feed rate change during the first feeding cycle in Figure 5-5.

## **5.4 Summary**

Chapter 8 illustrated though experimental results that fully functional gravimetric control algorithms had been developed, and most importantly that the principle behind using the volumetric characteristics of a material in gravimetric feeding does work.

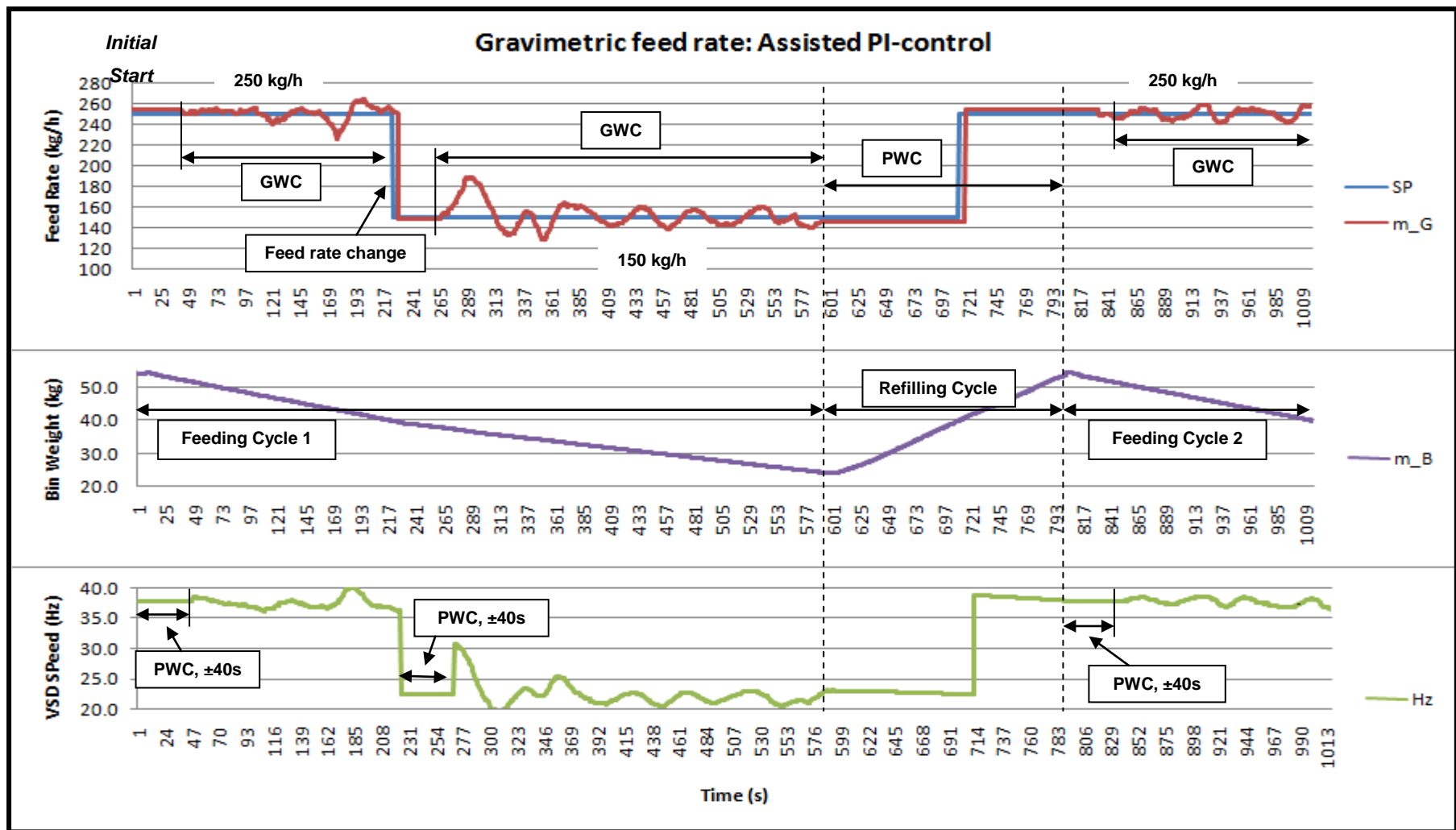


Figure 5-5: Graphical plot of the experimental results generated by the assisted PI-control code

## Chapter 6: CONCLUSIONS AND RECOMMENDATIONS

Chapter 6 presents a summary of the most important conclusions drawn from this study and makes recommendations for future work. This is then followed by a closure statement on the project.

### 6.1 Conclusions

Essential to any gravimetric feeding system is the weighing system signal processing process. Moving averages (MA) proved to be an effective signal conditioning method and was relatively easy to program with RSLogix 500. However, making use of MA's caused more problems than what they solved when used to filter the weight signal of the weighing system which was exposed to excessive mechanical vibrations. Thus great care should be taken when using moving averages for signal processing in gravimetric feeding systems.

The experimental results illustrated that the *volumetric characteristics* as obtained by the CP and the CC, can be used by the *predicted VSD calculations* and the *predicted weighing cycle* to successfully assist a PI-controlled gravimetric feeding system during both the *feeding-* and the *refilling cycle*. Most importantly, the experimental results illustrate that the selected control system with the develop control system software functioned correctly as a closed loop SISO feedback control system, as it achieved gravimetric feeding.

### 6.2 Recommendations

The experimental results which was generated with the code of the assisted PI-control algorithm, illustrated that a smooth transition is not always achieved between the *gravimetric weighing cycle* and the *predicted weighing cycle*. Therefore, extensive experimental testing and research must be carried out to refine the transition method between the *volumetric characteristics* and the *gravimetric weighing cycle*.

External disturbances are mostly caused by humans (i.e. somebody leaning on the feeder bin or bumping the feeder while passing by) or by moving equipment. These types of disturbances are the most difficult to compensate for as it is not recurring disturbances. Due to a pressing time limit on the project, the current control algorithms do not compensate for external disturbances. It is therefore crucial that extensive research is done to develop disturbance control algorithms to be incorporated into the current control system software.

### **6.3 Closure**

The aim of the project was to develop a PLC based control system with the applicable software for gravimetric feeding which could assist in the food and feed extrusion industries. From the results it can be seen that the main goals of the project have been reached. The developed test bench is fully functional and is delivered to and industrial standards. The project serves as a baseline for further research on gravimetric feeding systems.

## Chapter 7: REFERENCES

- Bayindir, R. & Cetinceviz, Y. 2010, "A water pumping control system with a programmable logic controller (PLC) and industrial wireless modules for industrial plants—An experimental setup", *ISA transactions*, vol. In Press, Corrected Proof.
- Dunning, D. 2006, *Introduction to programmable logic controllers*, 3rd Edition, Thomson Delmar Learning, New-York; USA.
- Interface, I. 2011, *Instrumentation*. Available: <http://www.interfaceforce.com/instrumentation-c-3.html> [2011, 02/16].
- McMillan, G.K. & Considine, D.M. 2004, *Process/Industrial Instruments and Controls Handbook*, 5th Edition, McGraw-Hill, [www.digitalengineeringlibrary.com](http://www.digitalengineeringlibrary.com).
- Nise, N.S. 2004, *Control Systems Engineering*, 4th Edition, John Wiley & Sons, Inc., USA.
- Omega Engineering Limited 2011, *An introduction to load cells, history, theory and best operating principles*. Available: <http://www.omega.co.uk/prodinfo/loadcell.html#8> [2011, 02/14].
- Riaz, M.N. 2007, *Extruders and expanders in pet food, aquatic and livestock feeds*, Agrimedia GmbH, Germany.
- Riaz, M.N. 2000, *Extruders in food applications*, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.
- Richard, C.D. & Robert, H.B. 2005, *Modern Control Systems*, 10th Edition, Pearson Education, Inc., USA.
- Rockwell Automation, I. 2011a, *MicroLogix 1400 Controllers*. Available: <http://www.ab.com/en/epub/catalogs/12762/2181376/2416247/9071972/9072580/> [2011, 02/17].
- Rockwell Automation, I. 2011b, *PanelView Plus Terminals*. Available: <http://www.ab.com/en/epub/catalogs/12762/2181376/1239781/1670480/1670482/> [2011, 02/21].
- Rockwell Automation, I. 2011c, *PowerFlex 40 AC Drives*. Available: <http://www.ab.com/en/epub/catalogs/36265/1323285/9467590/> [2011, 02/21].
- Shimmers, S.M. 1992, *Modern Control Systems Theory and Design*, John Wiley & Sons, Inc., USA.
- Svrcek, W.Y., Mahohey, D.P. & Young, B.R. 2006, *A real-time approach to process control*, 2nd Edition, John Wiley & Sons Ltd., The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.
- Tewari, A. 2002, *Modern Control Design with Matlab and Simulink*, John Wiley & Sons Ltd., England.

## **APPENDIX A: CONTROL ALGORITHMS**

**Appendix A** contains the main control algorithms that were developed for the control system software in block diagram form.

## Appendix A.1: Calibration algorithm

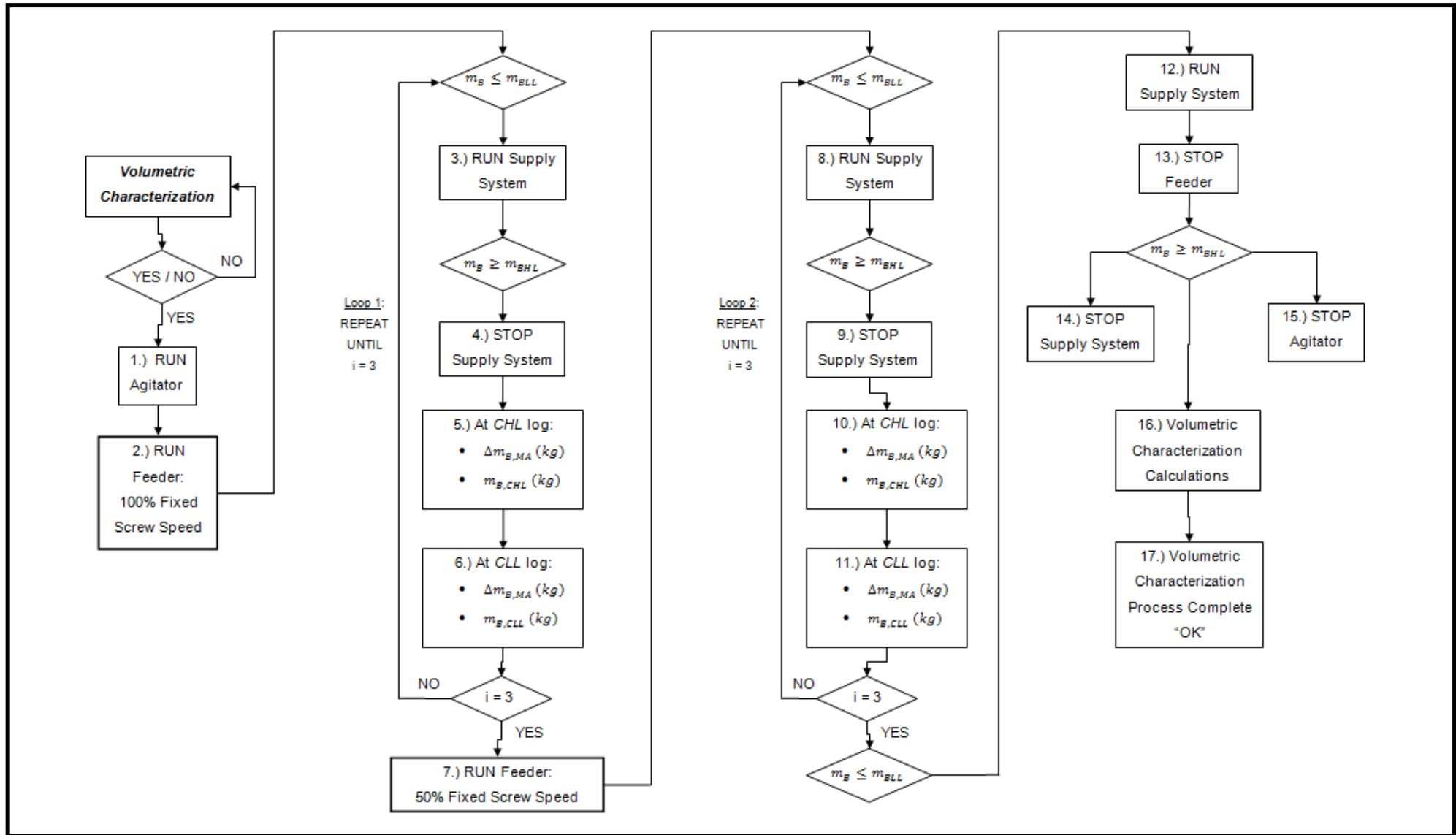


Figure 8-1: Schematic block diagram of the calibration algorithm

## Appendix A.2: PI-control algorithm

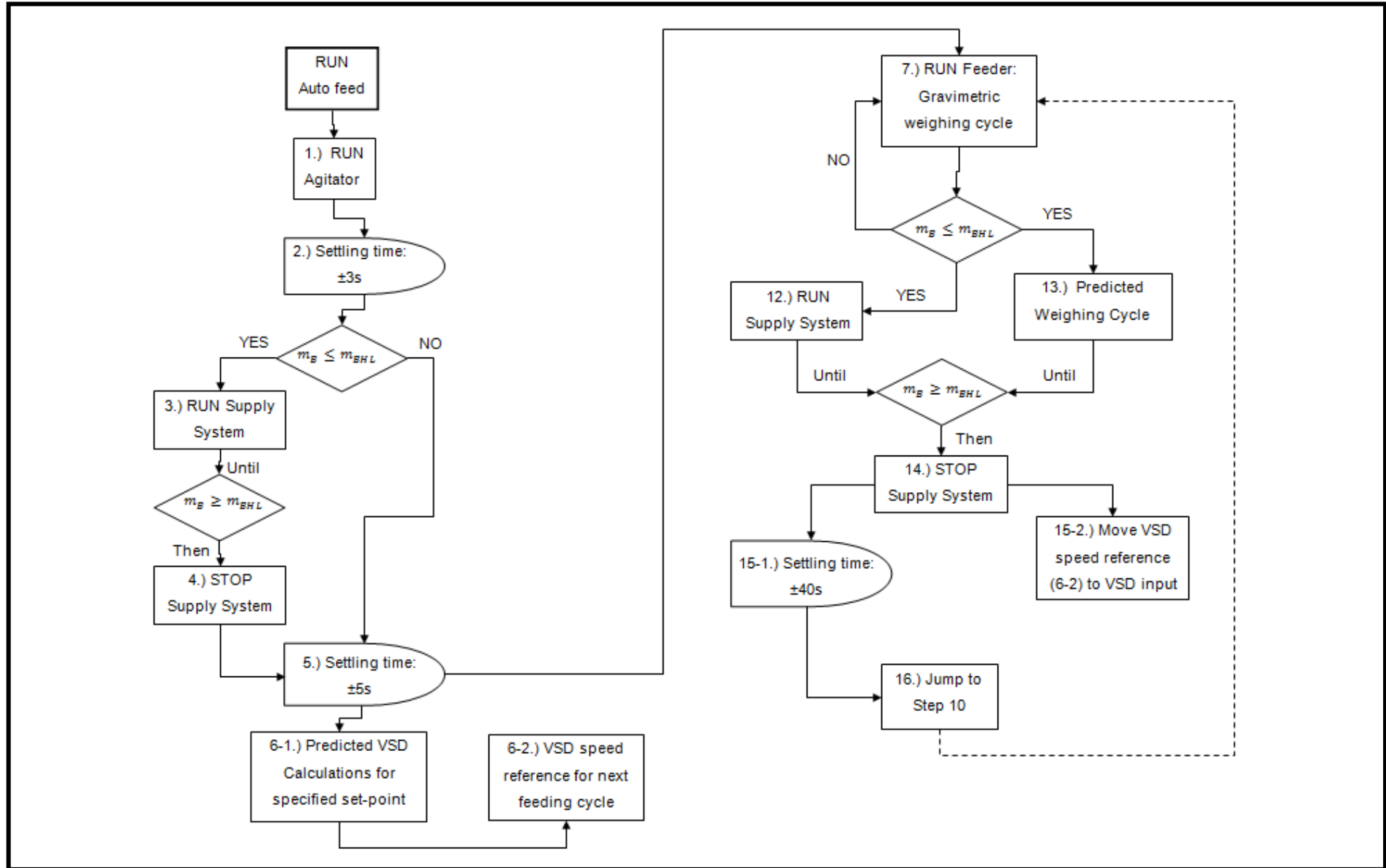


Figure 8-2: Schematic block diagram of the PI-control algorithm

## Appendix A.3: Assisted PI-control algorithm

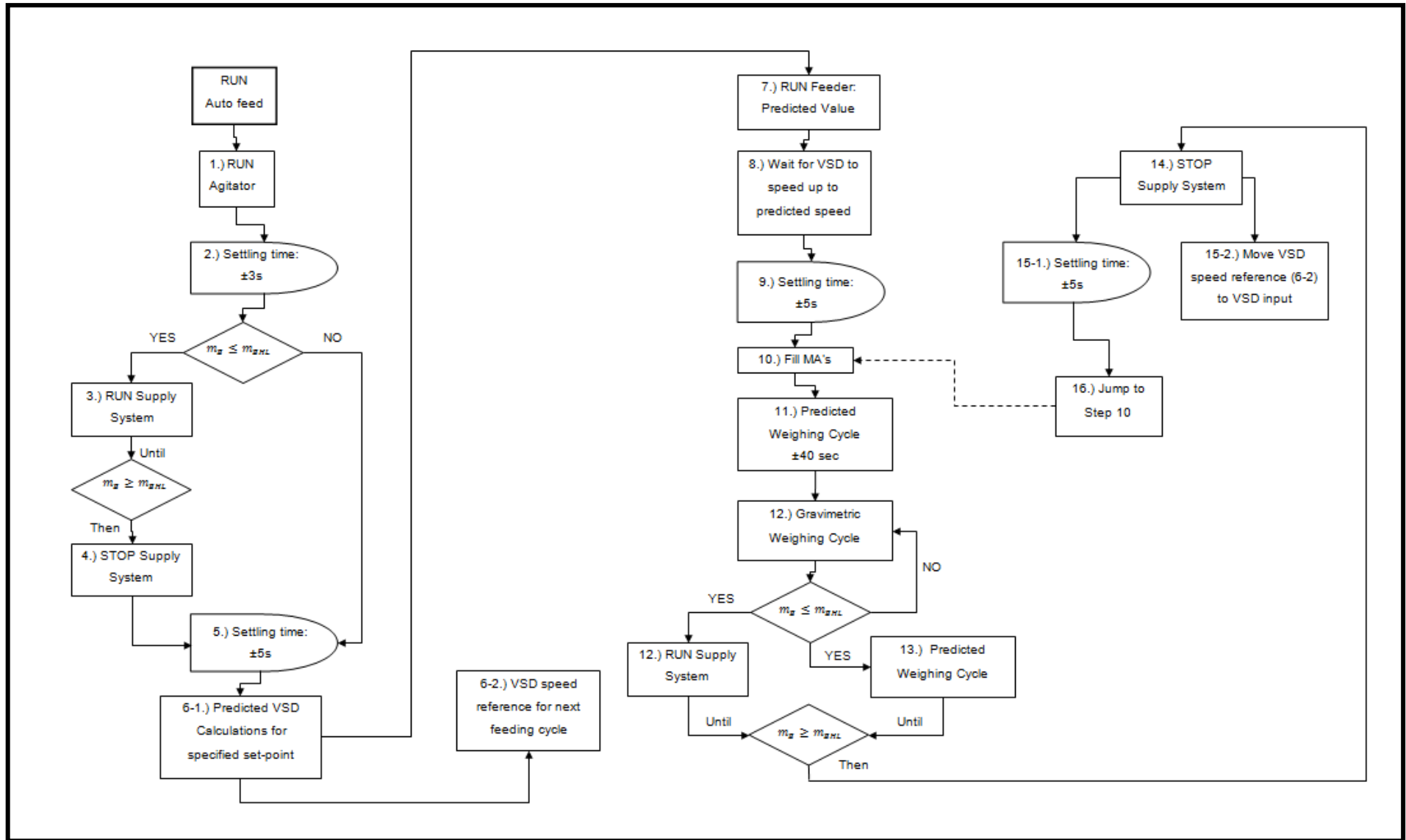


Figure 8-3: Schematic block diagram of the assisted PI-control algorithm

## Appendix A.4: Changed feed rate algorithms

### Feeding cycle - Changed feed rate algorithm: Assisted PI-control

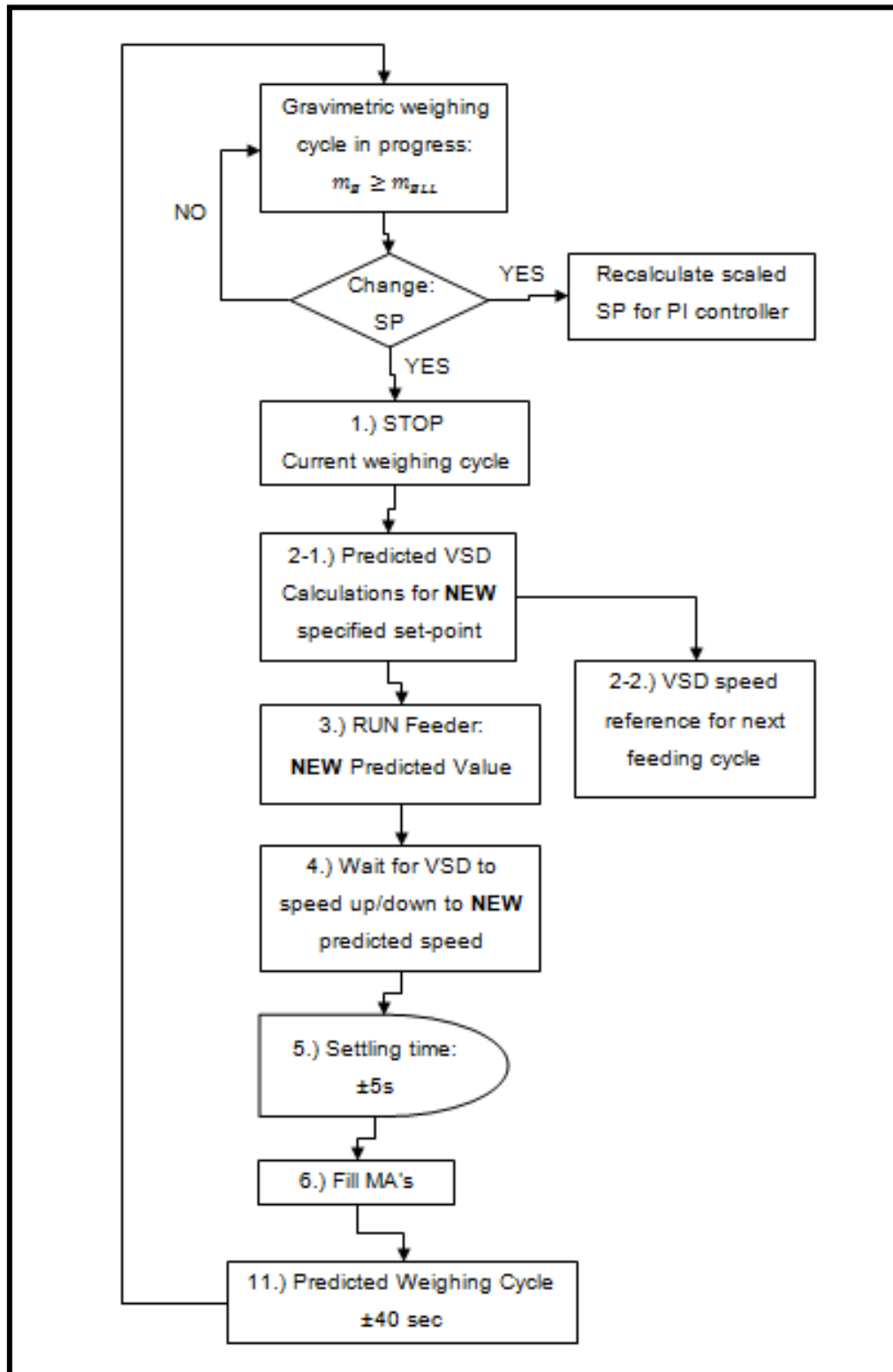


Figure 8-4: Schematic block diagram of the feeding cycle changed feed rate algorithm during assisted PI-control

**Feeding cycle - Changed feed rate algorithm: PI-control**

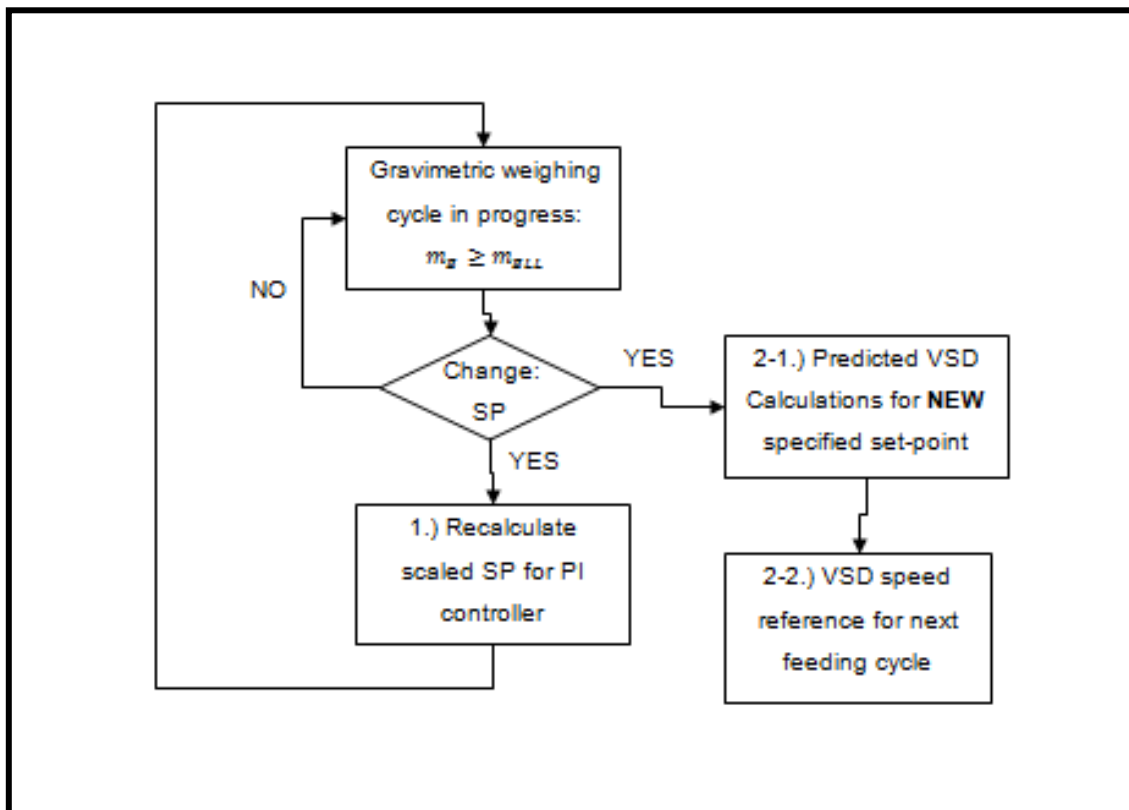


Figure 8-5: Schematic block diagram of the feeding cycle changed feed rate algorithm during PI-control

*Refilling cycle - Changed feed rate algorithm: Assisted - & PI-control*

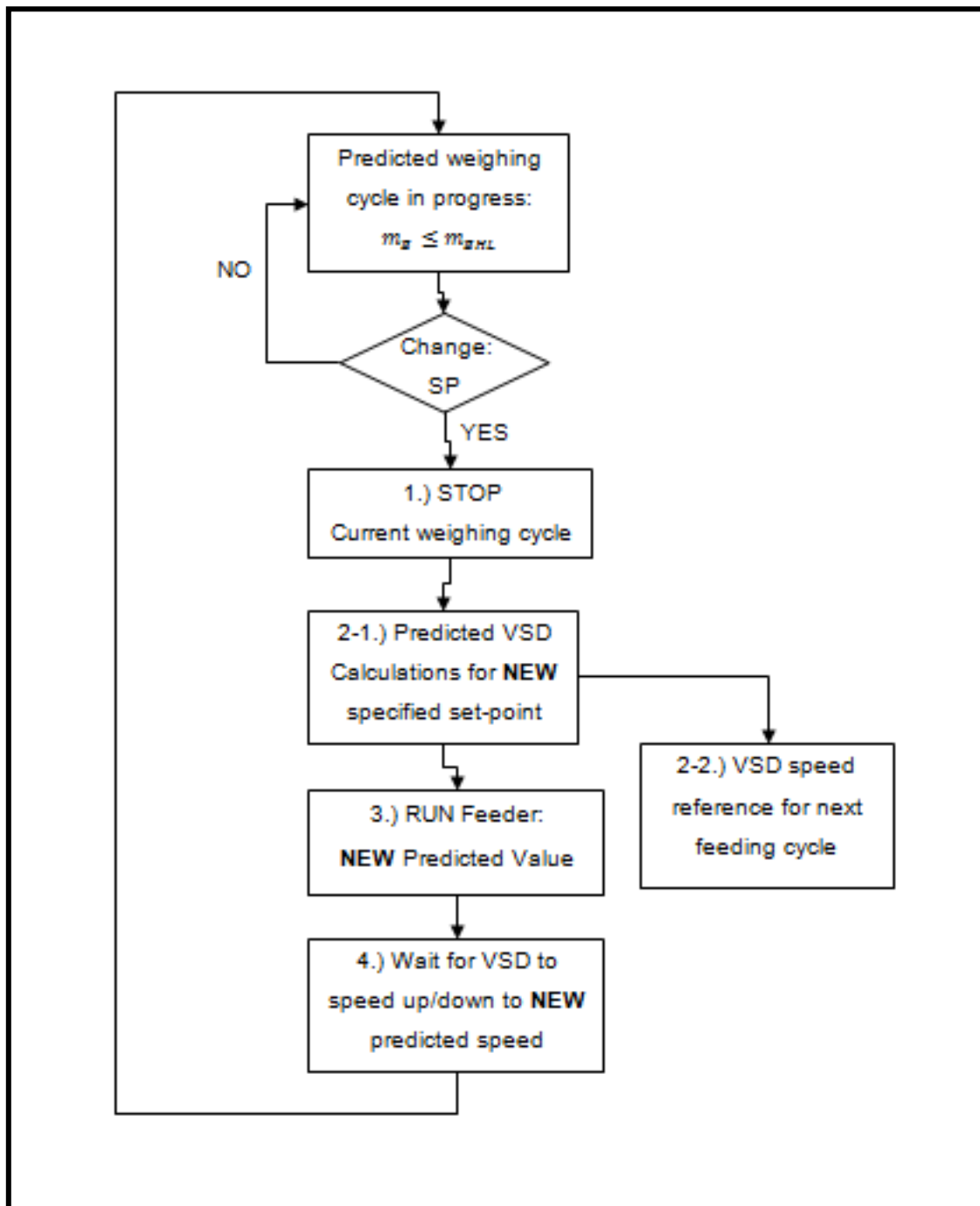


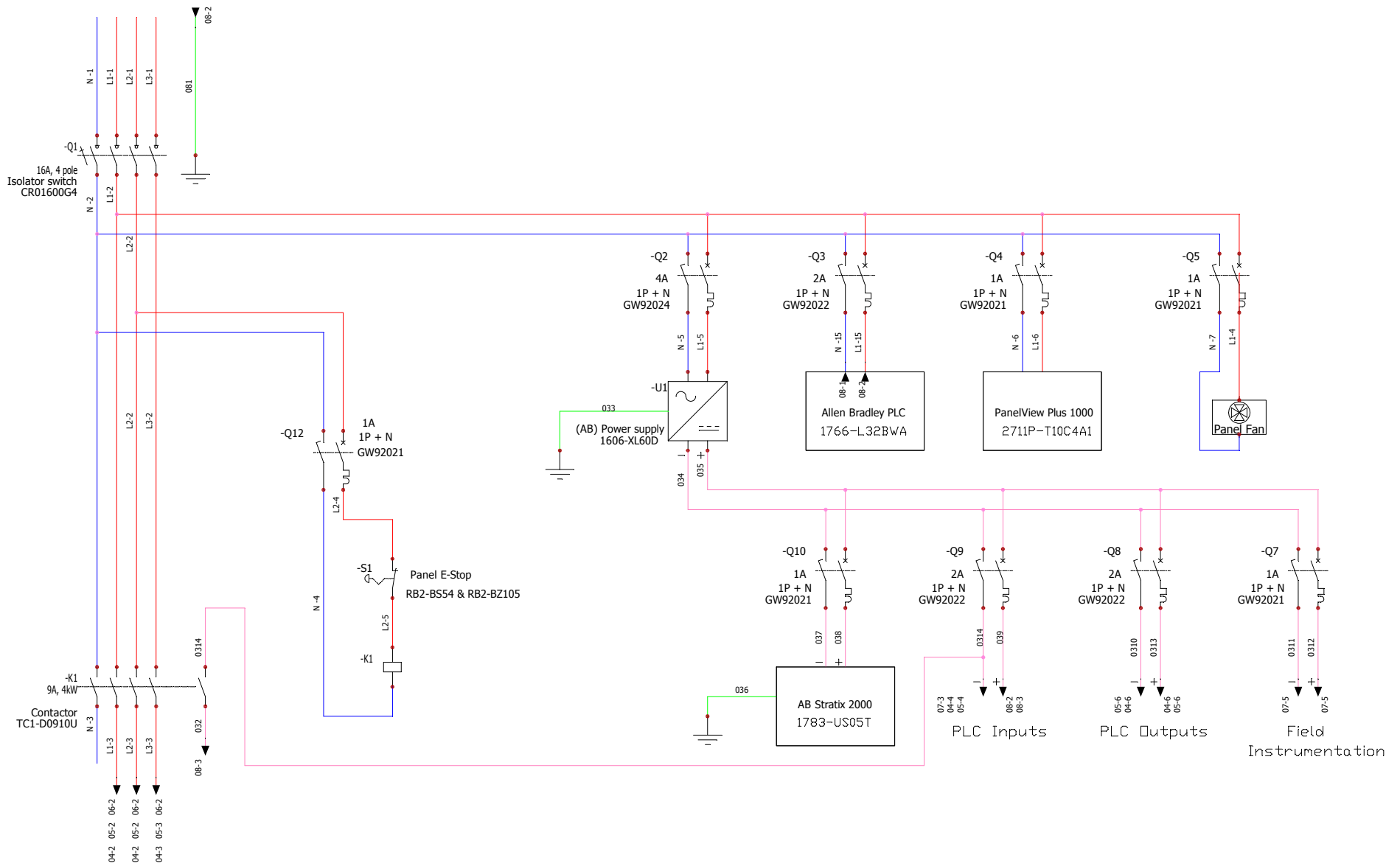
Figure 8-6: Schematic block diagram of the refilling cycle changed feed rate algorithm during both PI- and assisted PI-control

## **APPENDIX B: P&ID**

Presented in this Appendix is the complete Process & Instrumentation Diagram of the developed control panel.







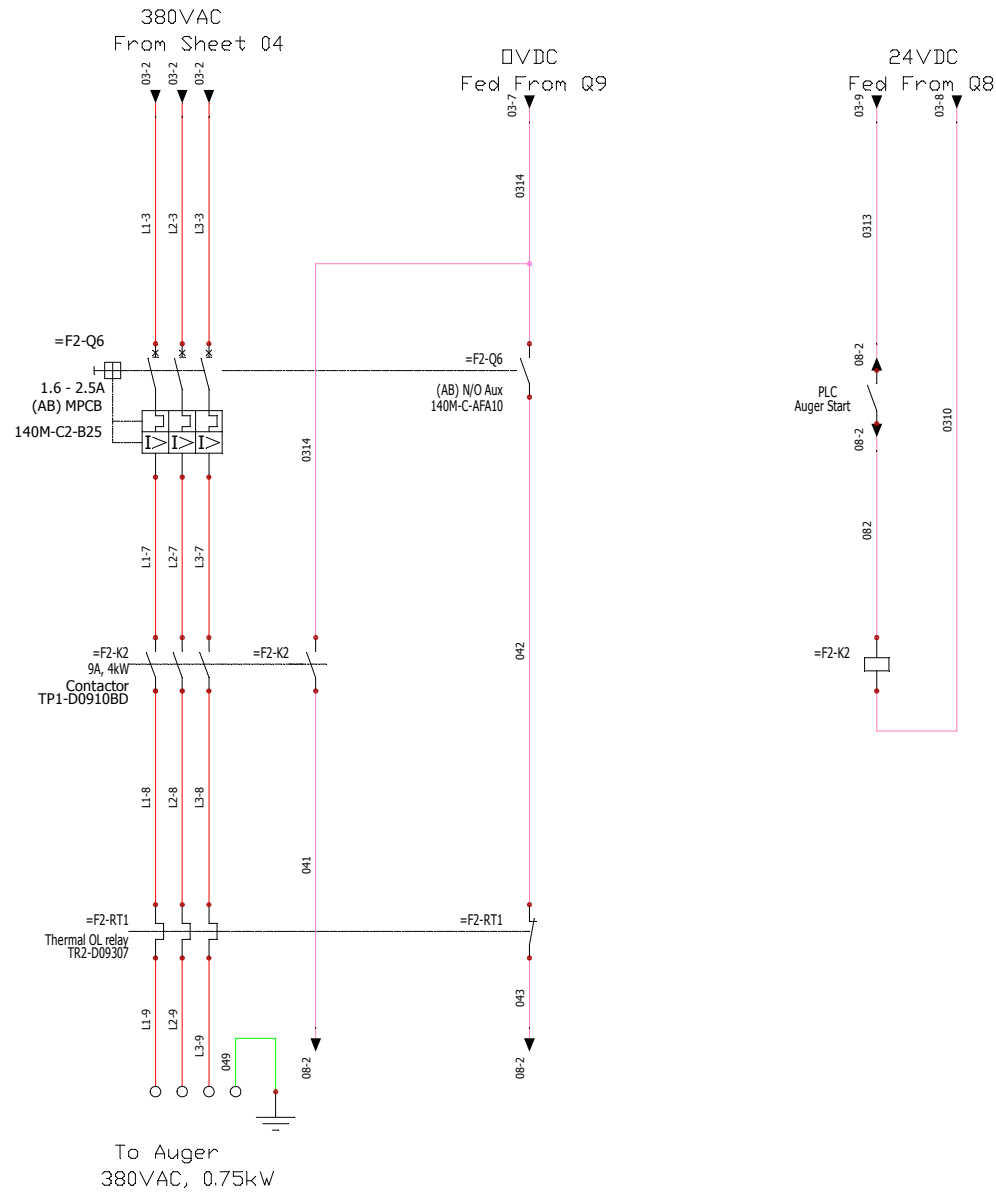
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 stefan@elecdoc.co.za

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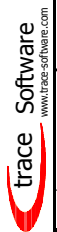
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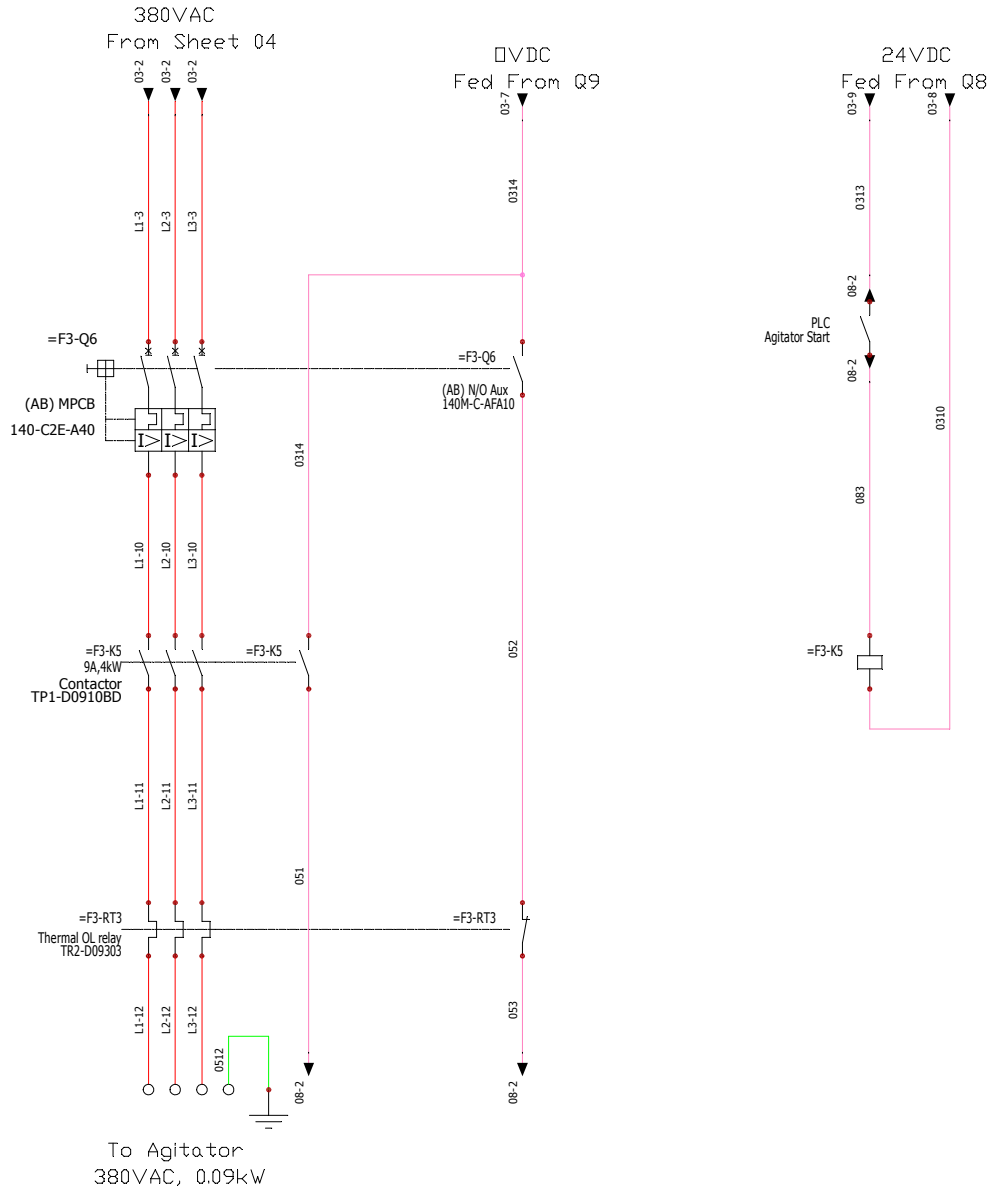
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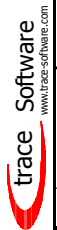


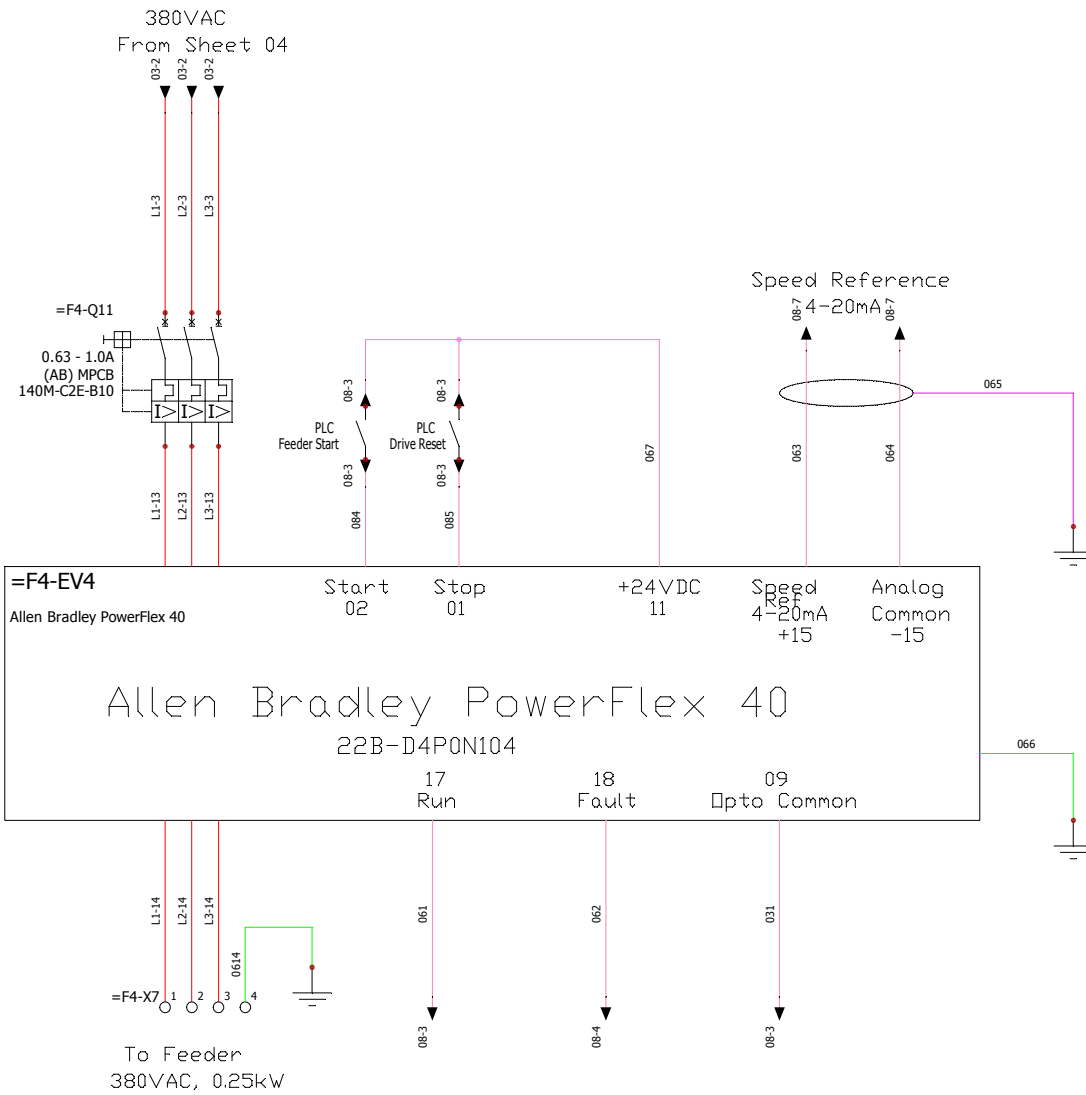


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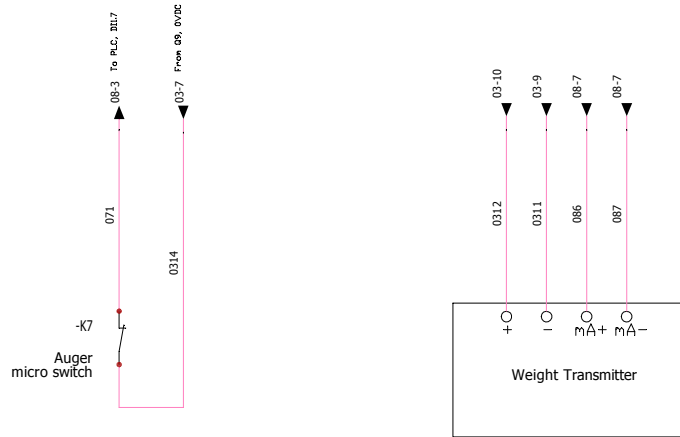
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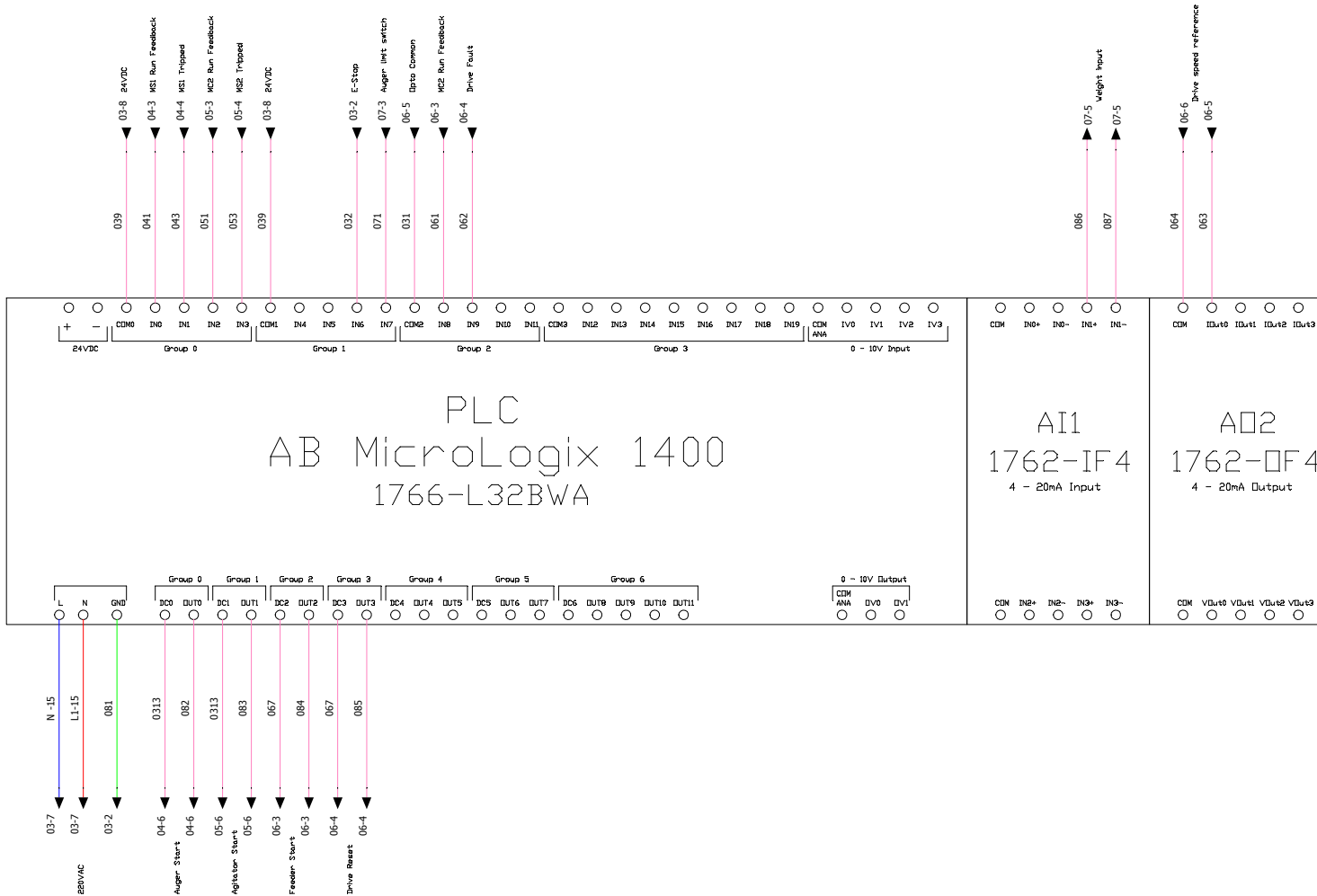
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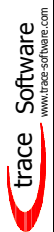
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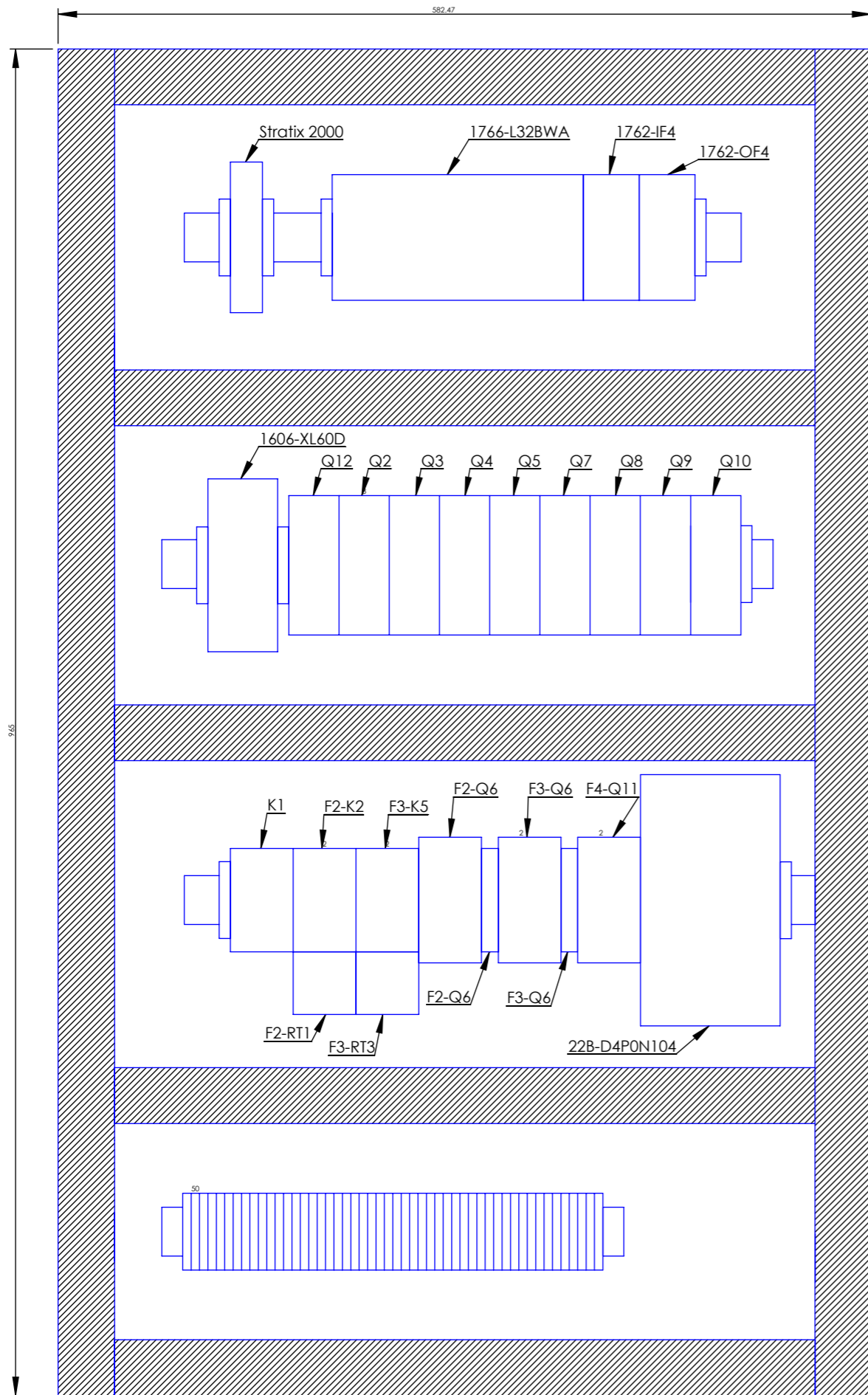
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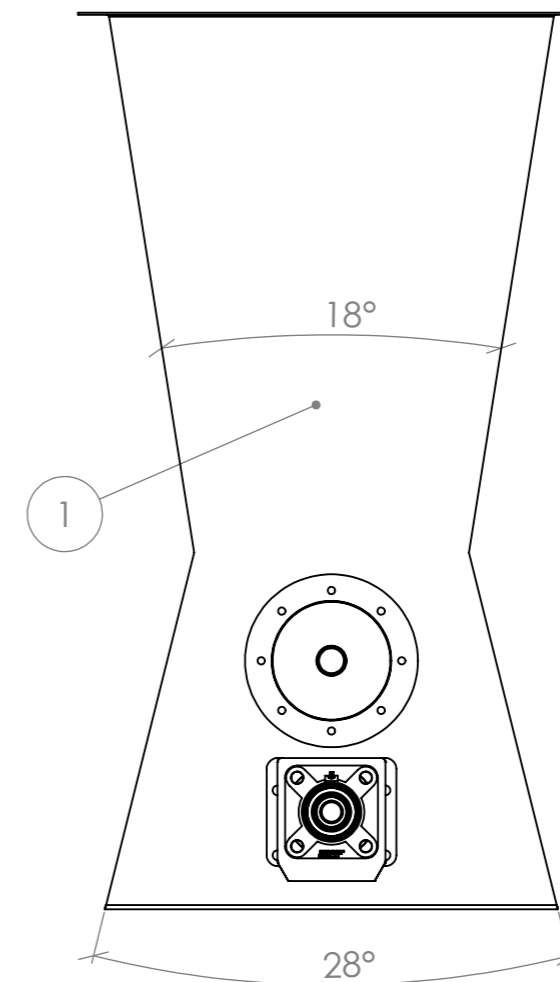
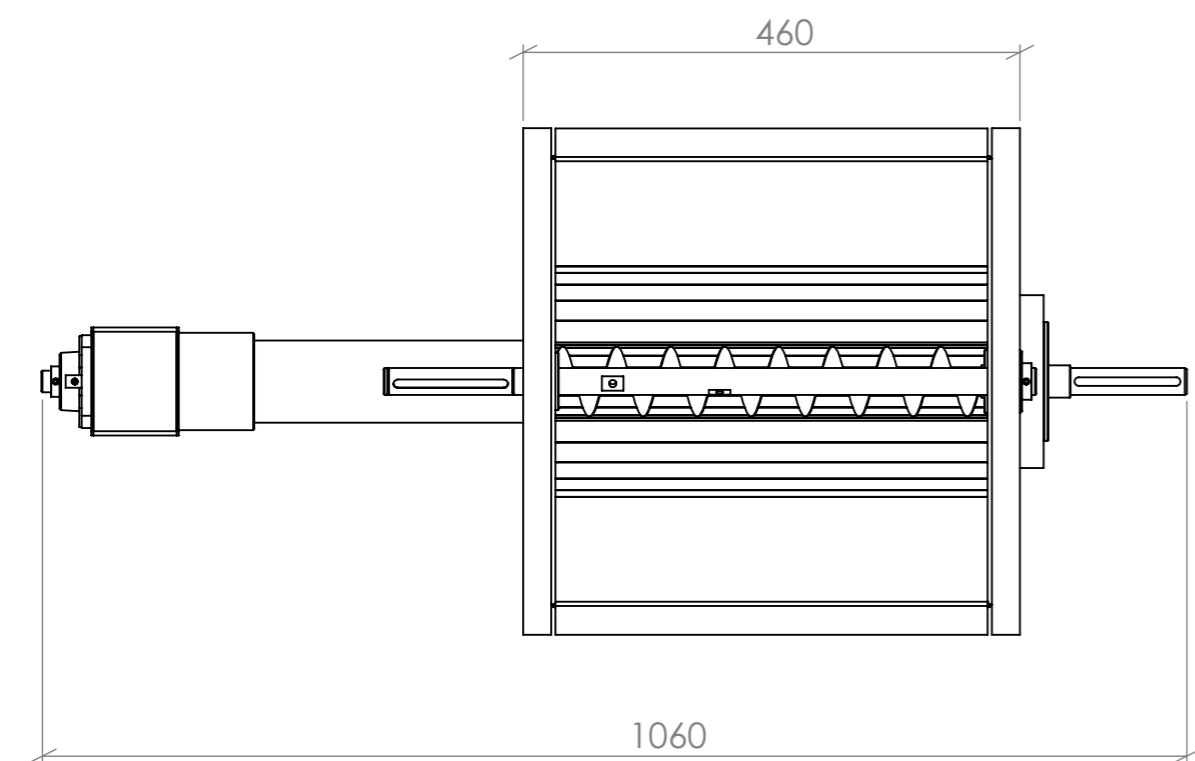
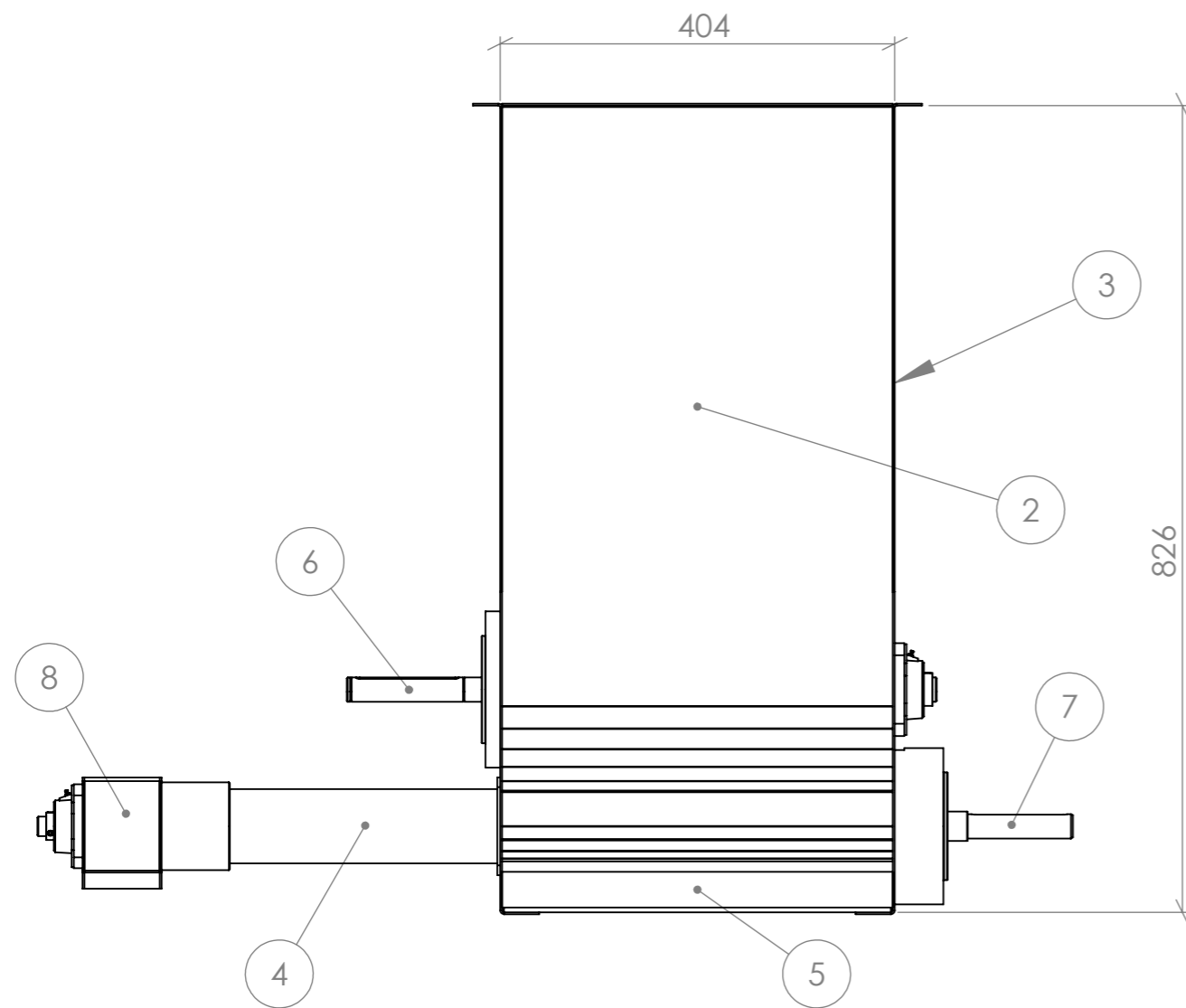




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## **APPENDIX C: ASSEMBLY DRAWINGS**

Presented in this Appendix is assembly drawing of the single screw feeder, the supply system and the weighing platform. Detailed drawings of the designs were produced for manufacturing purposes and are available but have not been included for proprietary reasons.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	FB-N-0103	FEEDER FRONT PANEL ASSEMBLY	1
2	FB-N-0005	FEEDER SIDE PANEL	2
3	FB-N-0104	FEEDER BACK BANEL ASSEMBLY	1
4	FB-N-0006	AUGER TUBE	1
5	FB-N-0007	CONNECTION PLATES	2
6	FB-A-0001	AGITATOR SHAFT ASSEMBLY	1
7	FB-FS-0101	SCREW CONVEYOR SHAFT ASSEMBLY	1
8	FB-FS-0103	END COVER	1

DRAWING NUMBER:

TEST BENCH - 0101

QTY:  
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DESCRIPTION:

ASSEMBLY DRAWING OF THE SINGLE SCREW FEEDER

DRAWN:

C JORDAAN

RAW MATERIAL:  
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ALL DIMENSIONS  $\pm 0.1$ mm UNLESS OTHERWISE SPECIFIED.

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2012/04/13

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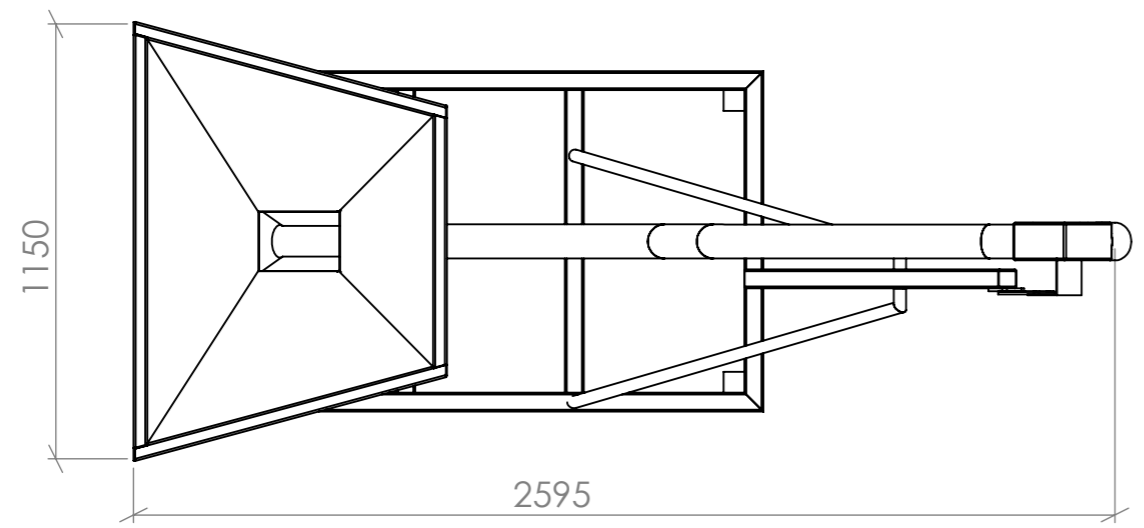
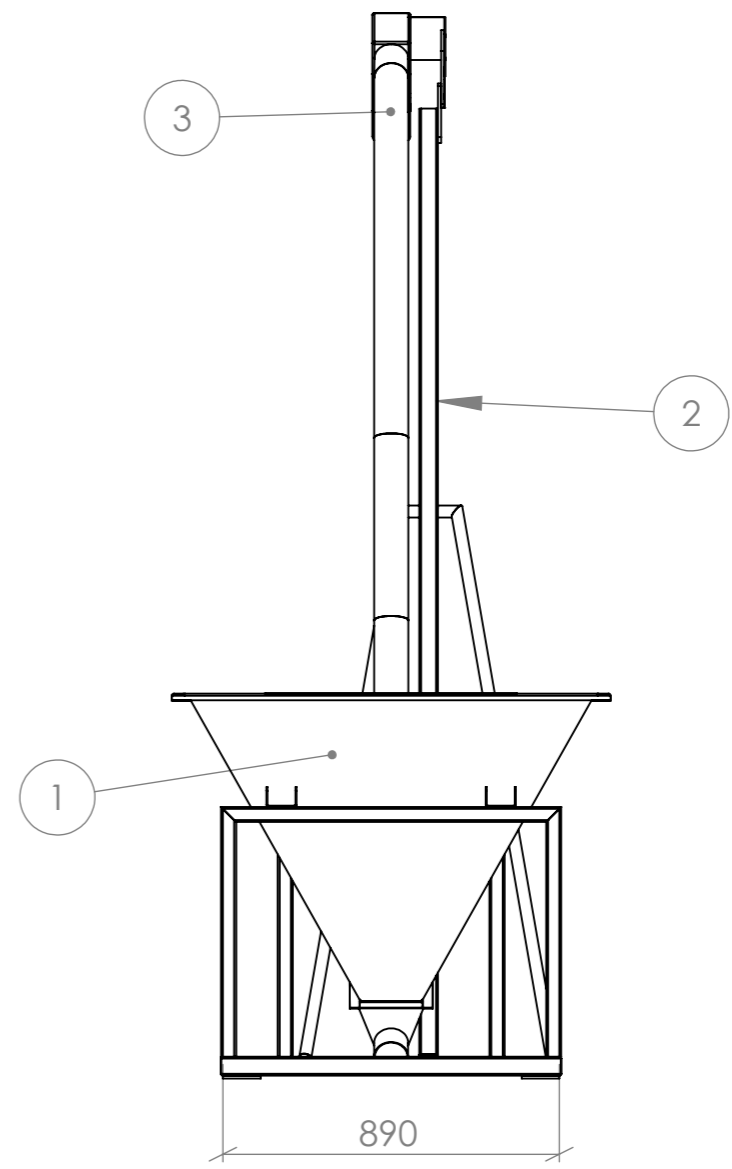
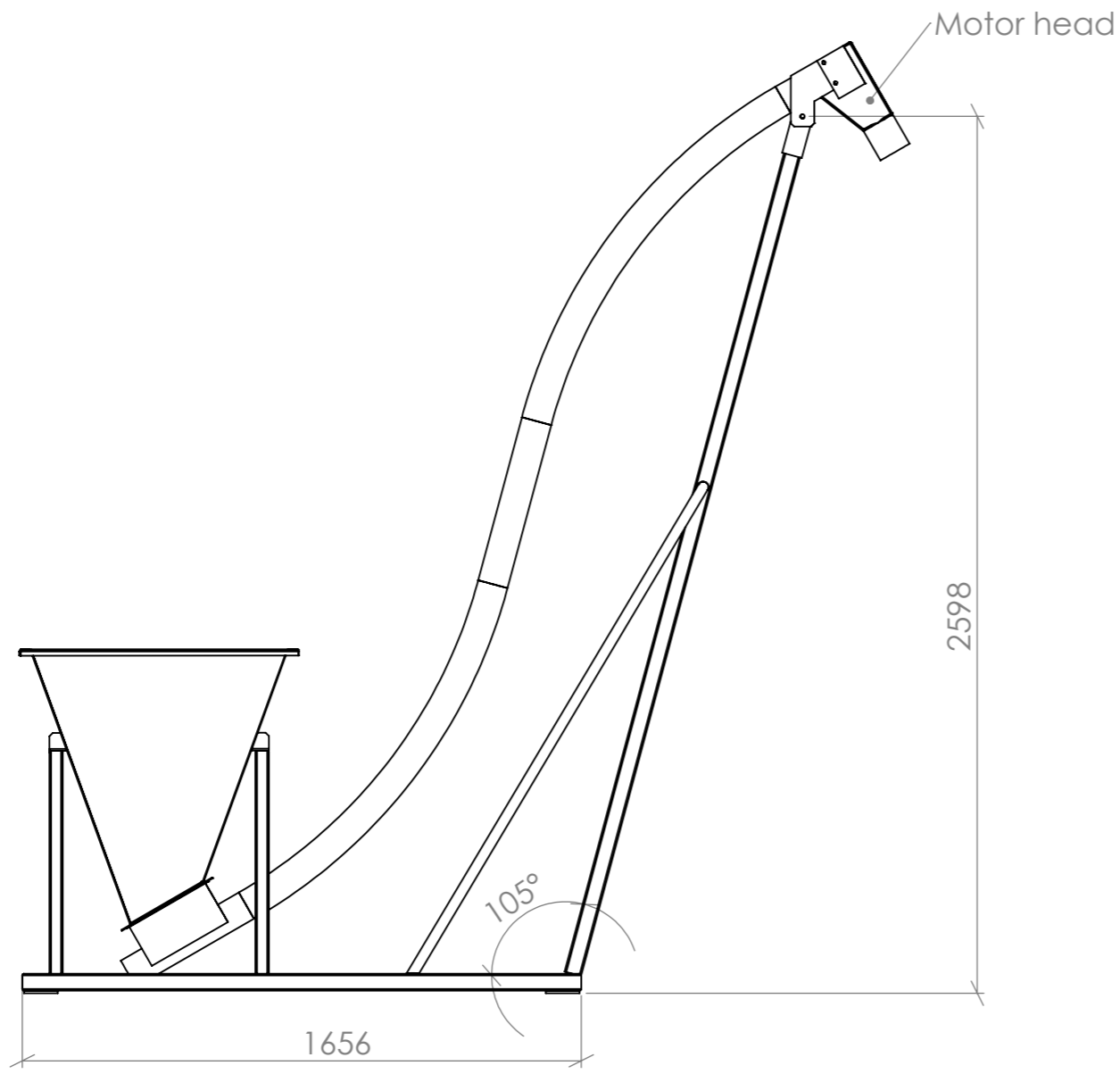
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2	FSC-F-0101	PORTABLE FRAME	1
3	Flexible Screw Conveyor	BIG DUTCHMAN CONVEYOR	1

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**OPERATION:**  
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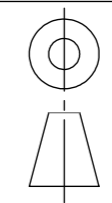
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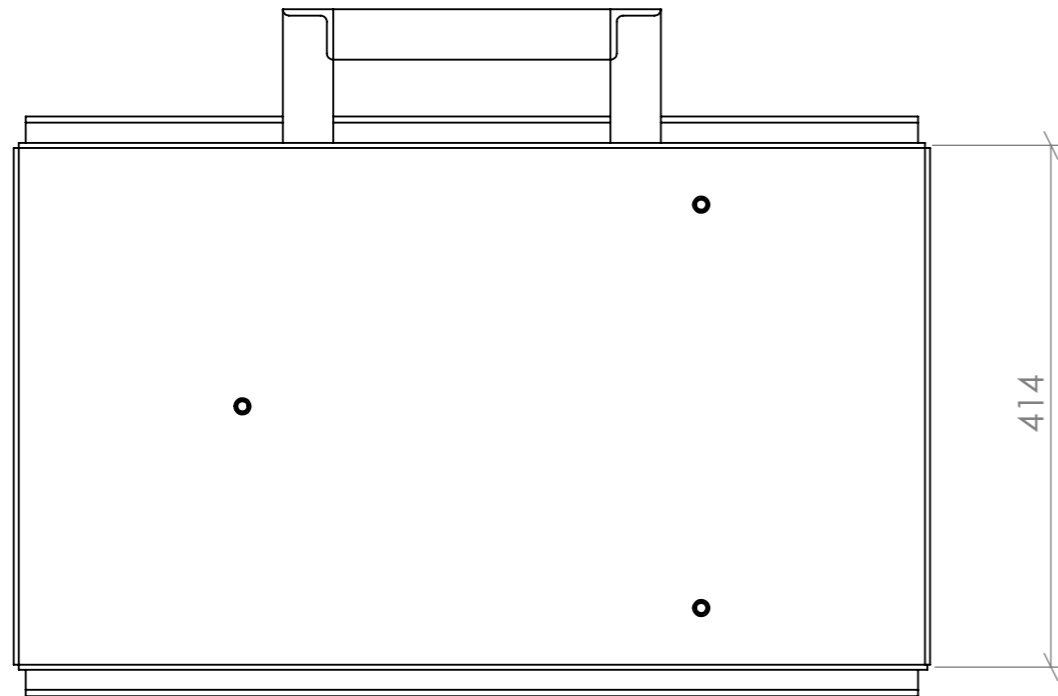
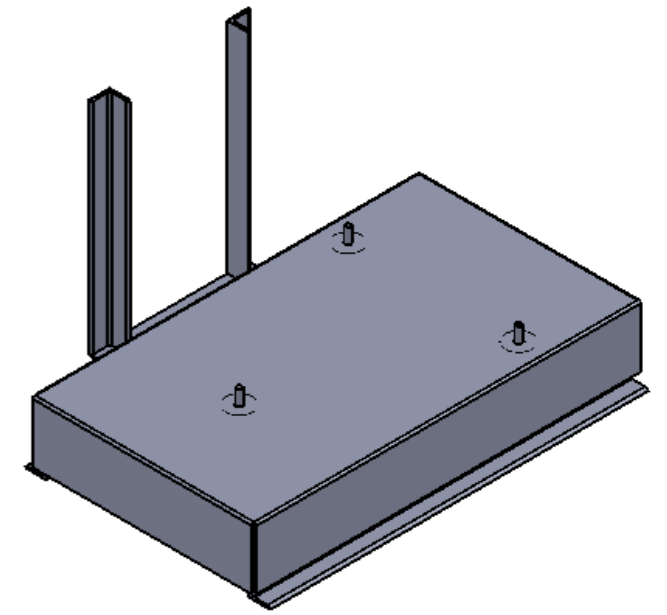
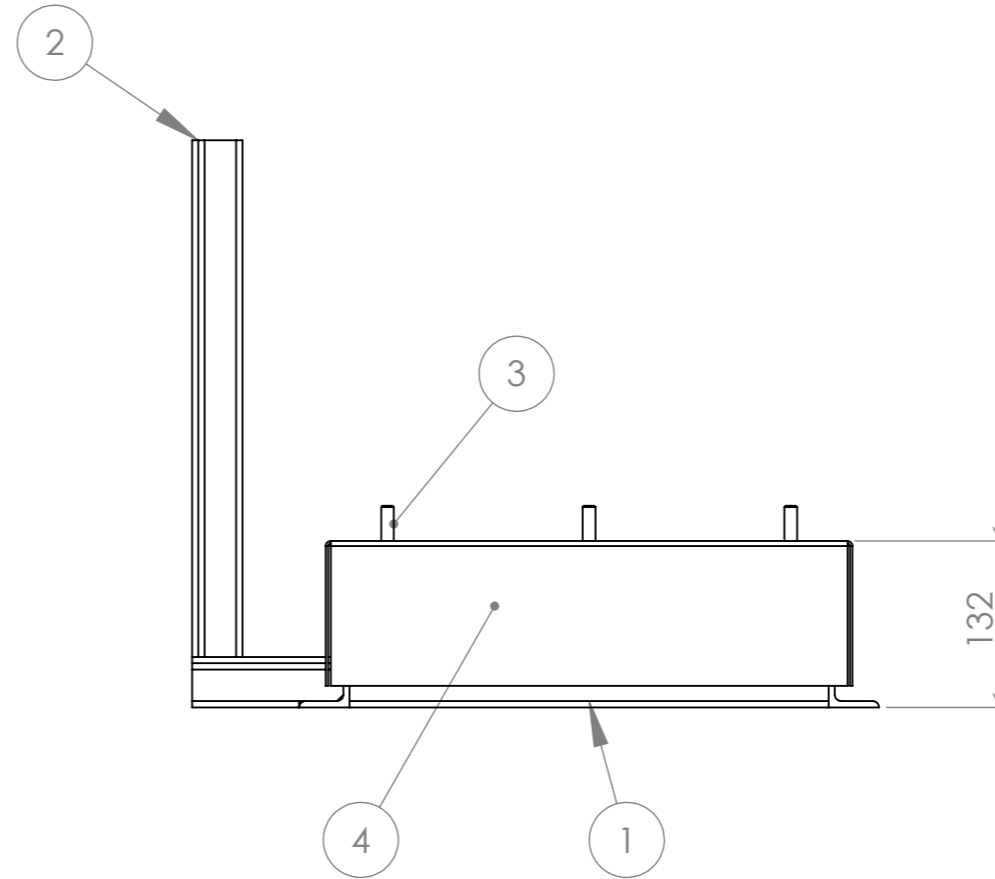
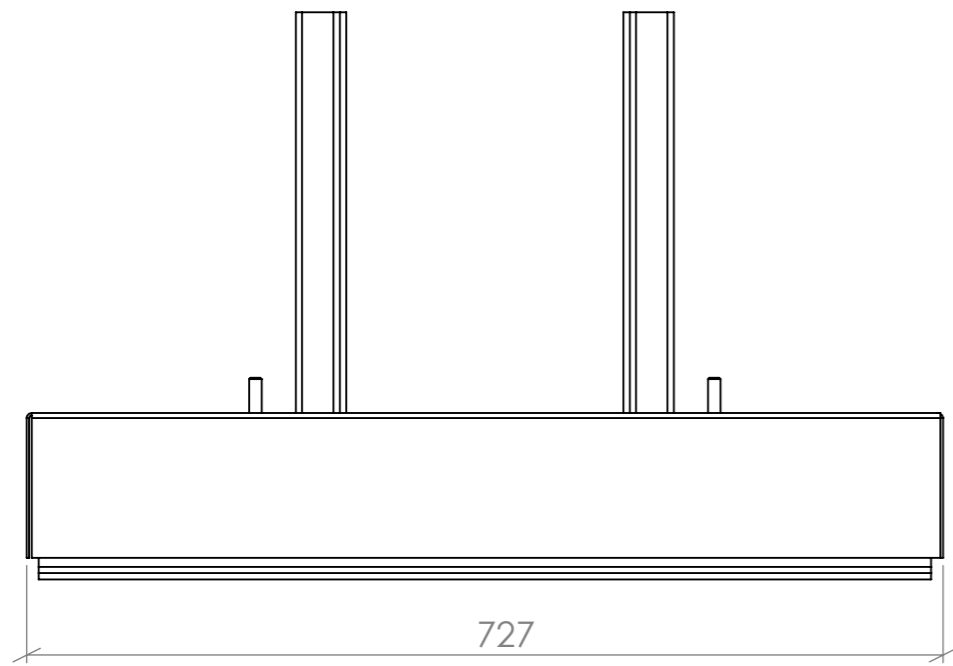
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ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
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2	FB-FR-0002	DISTRIBUTION BOX MOUNTING FRAME	1
3	LC-0100	LOAD CELL AND RUBBER MOUNT ASSEMBLY	3
4	FB-FR-0003	LOAD CELL COVER	1

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