Development of insect production automation: Automated processes for the production of Black Soldier Fly *(Hermetia illucens)*

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Thesis submitted for examination for the degree of Master of Science in Technology.
Espoo 31.12.2019

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ABSTRACT OF THE
MASTER'S THESIS

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Title: Development of insect production automation: Automated processes for the production of Black Soldier Fly *(Hermetia illucens)*

Date: 31.12.2019 Language: English Number of pages: 6+90

Department of Electrical Engineering and Automation

Professorship: ICP Automation System

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In recent years, Black Soldier Fly *(Hermetia illucens)* has received attention as an attractive approach for recycling biowaste into value products. The production of Black Soldier Fly (BSF) uses biowaste as the input feedstock for the growing of BSF larvae in order to produce nutrient-rich larvae feedstock products and organic fertilizers. However, most of the operations in BSF production are still carried out manually, which limits production volume. This makes BSF products less competitive than other traditional feedstock products. Thus, this thesis aims to develop automated processes for the mass production of BSF larvae.

In order to eliminate the dependence on manual work and to make feasible the industrialization of production, a six-step strategy was implemented. The sequence of steps was as follows: determining the requirements and specifications of the BSF production; calculating the desired capacity of processes; selecting machinery; designing automated processes; proposing a method of machinery integration; and designing state machines for automation software programming.

The solution developed here consists of four components: a list of machinery with capacity analysis; a designed floor layout and 3D visualization of all production processes; a proposed automation control system for the integration of machinery; and composite function blocks of IEC 61499 standard for automation software programming. This thesis shows that the availability of current technologies makes feasible the automation of the BSF production process. In terms of further work, the selection of processing machines should be verified; and both the programming of automation software and the use of simulation could improve the design of the production automation.

Keywords: Black Soldier Fly, BSF production, production automation development

Preface

My 6 months of thesis work has passed. The journey has brought me a lot of knowledge, experience, and emotions. First of all, I would like to send many thanks to Professor Valeriy Vyatkin for all the feedback and guidance during the thesis writing process. Your words and comments have helped me a lot in improving my final result.

Secondly, I would like to express my deepest thanks to Mr. Timo Salmi for all his great insights, and the experience and knowledge he shared related to automation projects.

Finally, I whole-heartedly send special appreciation to Mr. Tuure Parviainen and Mr. Matti Tähtinen. You guided me from the beginning and throughout the whole process. I learned a lot of interesting knowledge and skills from the work meetings and our time spent chatting. I also thank you both for the mental support you gave me during my writing process.

Without the support and guidance of all of you, I could not have completed this thesis with satisfaction. Once more time, thank you all very much.

Otaniemi, 31.12.2019

Vuong N. Vo

Contents

Glossary

5-DOL	Abbreviation for Five-Day-Old-Larvae
AC	Alternating current
AFD	Adjustable-frequency drive
Automation	State of being automatically operated
AVG	Automated guided vehicle
Biowaste	Biodegradable waste
BSF	Black Soldier Fly, *Hermetia illucens*
Controller	Device to compute received data to generate control commands
DC	Direct current
DCS	Distributed control system
Dry matter	The mass of the matter after all water has been removed
Emerging	The process of flies emerge from a pupa after pupation
Ethernet	Computer networking in a local area network
Flipper	Mechanism to turn over boxes
Frass	Leftovers of the rearing process
GUI	Graphical user interface
Hatching	The process of young larvae hatched from the egg
HMI	Human-machine interface
HVAC	Heating, ventilation, and air conditioning
I/O	Input/Ouput signals
IPC	Industrial personal computer
LAN	Local area network
LCD	Liquid crystal display
LED	Light-emitting diode
Material handling	Involving the movement and storage of materials
MMI	Man-machine interface
OIT	Operator interface terminal
OPC UA	Open platform communication unified architecture
PAC	Programmable automation controller
PC	Personal computers
PLC	Programmable logic controllers
Prepupa	Last larval stage before pupating
Pupa	The metamorphosis from larva to adult fly happens
Rearing	The process of growing insects
RFID	Radio-frequency identification
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition
SCARA	Selective compliant assembly robot arm
State machine	Diagram of stable states indicating the behavior of a system
VDC	Volts direct current
VFD	Variable frequency drive

1 Introduction

In recent years, edible insects have attracted considerable attention as a potential alternative source of protein for humans and livestock, due to their high nutritional content paired with a minuscule ecological footprint [1]. Insects are rich in protein and contain a healthy amount of fats, minerals, and vitamins [1], [2]. Insect rearing also requires less farmland, less water and emits a lower carbon footprint than conventional meat products [2]. More impressively, Black Soldier Fly larvae, an edible insect, can be fed using organic waste and bio by-products, such as agriculture waste, food processing by-products, and kitchen leftovers [3], [4], [5]. These benefits provide us with a sustainable and promising solution to address several urgent global challenges at the same time: ensuring food security, obviating the waste crisis and reducing the negative impacts of livestock industries on the environment.

Recently, much work has been devoted to developing methods for mass production of insects [7], [3]. However, these approaches are labor-intensive, as most of the processes are performed manually. This limits the volume produced and the quality of the product. These limitations make insect products less competitive in price and quality compared to other meat- and fish-based products. Moreover, human involvement creates a significant risk of contamination during production, which negatively impacts the efficiency of insect growing.

Automation has been seen as a vital factor in modern industrial production due to its benefits in optimizing product quality and productivity as well as reducing the dependency on manual work. It is an important approach for bringing new product concepts to mass production and profitable business. Automation has been applied to increase the efficiency of insect rearing in several facilities [7]. However, these automation approaches have only focused on the automated control of abiotic conditions such as temperature, humidity, CO_2 and lighting, thus ignoring numerous important aspects to monitor and automate the processes of insect production [7]. Currently, there are several factories around the world such as AgriProtein (South Africa), Protix (Netherlands), Phoenix Worm (USA) and JM Green (China) that have enabled mass production of Black Soldier Fly (BSF) larvae. Unfortunately, the automation systems developed for these mass productions are restrictively revealed. Although automation approaches have proven to be successful in such factories, few studies have attempted to automate the processes of BSF production.

Thus, this thesis aims to propose automated processes for the mass production of Black Soldier Fly larvae in order to eliminate the dependency on manual work. Based on the manual production process presented in a step-by-step guide published in [3], a six-step strategy is proposed for transforming operations in the manual process into elements of industrial automation, which will be applied to automate BSF production process:

1. determining the requirements and specifications for BSF production,
2. calculating the desired capacity of the processes,
3. selecting machinery,

4. designing automated operations for BSF processes,
5. proposing a method for machinery integration, and
6. designing state machines for automation control.

The thesis is restricted to basic technical information obtained from suppliers' quotations on the machinery. Since detailed I/O lists of machines and devices are not available, fully programmed automation software remains outside the scope of this thesis. The thesis will only focus on the selection of machinery, the structural design of the automated processes, the control system to integrate the machines and the creation of IEC 61499 standards function blocks for future software development. Moreover, climate control of the rearing warehouse is not considered in this thesis, since it can be implemented using an HVAC system.

The remainder of this thesis is organized as follows. Chapter 2 briefly provides the background of Black Soldier Fly production. Chapter 3 reviews the literature on industrial automation. In Chapter 4, a methodology is proposed to develop automated processes for production. Results and discussion of the development are presented in Chapter 5. Conclusions and suggestions for future work are discussed in Chapter 6.

2 Black Soldier Fly production

Understanding about BSF is vital for the development. In this chapter, the natural characteristics of BSF are given in Section 2.1 and the typical BSF production process is described in Section 2.2.

2.1 BSF life cycle and development conditions

Black Soldier Fly, *Hermetia illucens*, is an edible insect of the dipteran family. It can be found in nature worldwide and has been captured and reared in many countries across Europe, Asia, Africa, and America. Similar to many types of insects, BSF undergoes different stages in its life cycle. The life cycle of BSF can vary from six weeks to several months depending on environmental conditions and the availability of food sources [5], [3]. Figure 1 shows the main life stages of BSF: egg, larval, prepupal, pupal and adult stages.

Figure 1: Life stage of the BSF [3].

The life cycle starts with the egg-laying of BSF fly. A female fly lays about 600-900 eggs and dies soon after that. On average, eggs are hatched after four days [3], [4]. Once hatched from the eggs, the emerged larvae craw to seek surrounding organic matter for food. The development of the larval stage takes about 4 weeks to 5 months, depending on food availability and environmental conditions [4]. After undergoing the larval stage, the larvae change their color from beige to dark brown [4] and start the prepupal stages. During this period, prepupae move away from food sources to shaded areas to start the process of pupation. The pupation takes about 2 to 3 weeks [3] for the emerging of flies. After emerged from pupae about 2 days, the flies start mating and lay eggs after 2 days more [5], [4]. The lifetime of adult flies is fairly short. They die after 1 week [3], [5] and the cycle ends.

The development of BSF highly depends on the environmental conditions such as temperature, humidity, light intensity, quality and quantity of available food [4]. The warm climate is a key factor. It has been observed that the development occurs in the temperature range from 24 °C to 35 °C: about 27 °C to 30 °C ideal for the egg hatching [4], about 24 °C to 30 °C for the larvae development [3] and between 25 °C and 35 °C for the mating of flies [3]. Relative humidity also significantly affects the development of BSF. It was reported in [6] that when the relative humidity is increased, egg hatching and adult emergence rates are raised while the duration of larval growth is shortened. BSF behavior also is influenced by light intensity. According to [3], [5], the flies are attracted to lights and prefer to mate under sunlight in the morning. Meanwhile, larvae and prepupae tend to escape from light and always crawl to find shaded and dark places. Lastly, the availability and quality of food affect the life cycle of BSF. Although BSF larvae obtain nutrients from various organic matters such as decaying vegetables and animal manure [6], substrates which rich in protein and carbohydrate and has a water content between 60% to 90% has been seen as the ideal food sources for the larval development [3], [5].

2.2 BSF production process

In recent years, BSF has been received attention as an attractive approach for recycling biowaste into value products. During larval development, BSF larvae can be fed with various types of organic waste such as municipal organic waste, food waste, and animal manure [3]. The volume of the waste can be reduced up to 80% [4] and the pathogens such as *Salmonella* and *E.coli* in waste are also decreased [7]. Besides, the BSF larvae contain high nutritional content with about 35% protein and 30% crude fat [3]. Therefore, they can be treated as a rich nutrient source for animal feed. The larvae can be fed directly to chickens and fishes or be processed into protein concentration and extracted oil. BSF protein has been confirmed as an alternative ingredient to soybean and traditional fishmeal in feed production by commercial products in the markets [8], [9]. Extracted oil can be used as a substitute for fish oil and soybean oil in agriculture feedstock. This high-quality liquid fat can also be used in cosmetics, pharmaceutics[8] and biofuels production [10]. Another product of BSF larvae rearing is frass. Frass is the leftover [3], [4] of the waste conversion which can be used as fertilizer or soil additive in agriculture. Figure 2 presents several products from BSF production.

Because of above benefits, it is valuable to transform the BSF rearing into mass production. The feasibility of BSF mass production has been proved in [7], [3] and [4]. Several production methods of BSF have been reviewed in these papers. However, they are still primitive and are implemented in small facilities for local needs. The rearing process is intensive in manual work. Although, machines and equipment have been used to handle most heavy tasks, the level of human involvement is still majorly high. This leads to a limited produced volume, makes BSF products less competitive in price and quality compared to other traditional feedstock products. In recent years, BSF production has been translated into industry levels with several large factories in South Africa, Netherlands, USA, China, and East Asia. Mechanization and automation have been applied to increase the capacity of production as well as to increase the consistency of product quality. However, as the production of BSF has been seen as an attractive industrial enterprise, the design of production automation is strictly revealed.

Figure 2: Products of BSF production: a. Wholemeal alive, b. Concentrated protein, c. Frass organic fertilizer, and d. Extracted oil

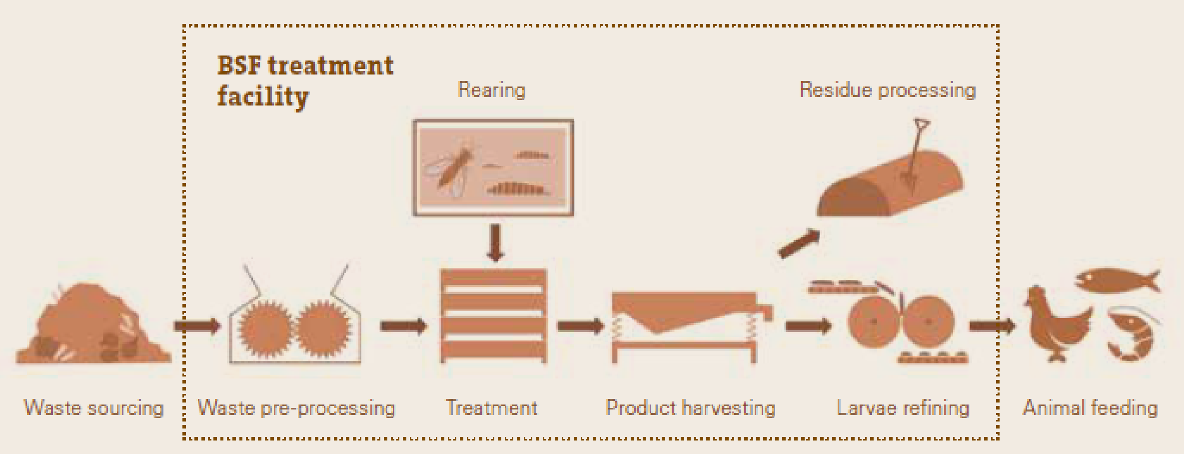


Figure 3: A suggested BSF treatment facility [3].

A typical BSF production process was explained in [3] and [5]. The production process treats biowaste as the input feedstock for the growth of larvae to produce nutrient-rich larvae products and organic fertilizer. Figure 3 demonstrates the main processing units of the production process. Five main processing units include:

- waste receiving and pre-processing,
- BSF rearing,
- BSF waste treatment,
- product harvesting, and
- post-treatment unit.

In the waste pre-processing unit, biowaste is received and pre-processed into a suitable feedstock for the larvae. The unit involves quality control of the waste, a reduction of waste particle size and a blending or dewatering to create a suitable moisture feed mixture. To favor the feeding of larvae, the feedstock is prepared as such it contains no hazardous material, has the particle size of 1-2cm in diameter with the water content between 60% to 90%. BSF rearing is where BSF is reproduced to provide 5-day-old larvae (5DOL) for the seeding on the waste feedstock. This rearing unit involves fly emergence and mating, egg hatching, and young larvae feeding. After 5 days of growth in the BSF rearing site, the young larvae are transferred to the BSF waste treatment unit to be fed on the biowaste in containers and to grow while decaying the waste into the residue. Shortly before turning into prepupa, when the larvae reach their maximum size, they are separated from residue in the product harvesting unit. Two separation methods to harvest larvae were introduced based on the water content of harvesting substances, including non-shaking screening for wet residue and shaking screening for crumbly waste residue. The harvested residue and larvae can be then refined into final products in the post-treatment unit. Depending on the required by the local market demand, larvae are kept alive, to be dried or be pressed for the extraction of fat and protein. Residue can be refined by composting or feeding to fuel production.

In [3], a step-to-step guide for the production activities in each processing unit was introduced. However, most of the operations in these processing units are still carried out manually. Figure 4 shows an example of manual activities in the production. The waste filling and larvae seeding into containers are performed manually using primitive equipment such as scales and buckets. The stacking of rearing boxes on pallets is also implemented by hands which is absolutely labor-intensive. As the production process contains many manual tasks, the processing capacity is fairly low and is difficult to be industrialized on a large scale. According to [3], the facility is only able to treat one ton of waste per day, thus the produced volume of larvae is fairly low. Moreover, manual handling large amounts of biowaste, in the long run, may harm worker's health and the workers can also contaminate the production. Therefore, it is necessary and valuable to eliminate direct human labor in the production process.

Figure 4: Manual seeding 5-DOL and filling waste [3]

3 Industrial automation

Similar to other production industries, BSF production can be automated to reduce the manual labor as well as to increase the productivity and capacity of the production. This chapter will briefly review the literature on industrial automation and its essential elements to investigate the availability of technologies for production automation development.

3.1 Automation and classifications

Automation is defined as the state of being automatically operated of equipment, machines or processes[11]. To eliminate human interaction as well as to improve the consistency and accuracy of the operations, automation has been seen as an inevitable trend and strategy in every aspect of life. This section will give an overall introduction to automation and will discuss the classifications of automation in the industry.

Humans tend to avoid using physical strength to perform repetitive hard work. This leads to the advent and development of self-operated powered instruments or machines very early in history. Along with the history, early automated machines had been introduced for example waterwheels or windmills [12], [13], [14] (see Figure 5 and 6). These two archaic devices proves that people from the immemorial time were aware of the benefits and the needs of becoming more self-operated and less human involvement in daily life and production activities. However, until the 1940s, the term *automation* was first coined by a Ford Motor Company engineer who described various systems where automatic actions and controls were executed by using electromechanical devices, relays and timers to substitute for human effort and intelligence [15], [16]. Nowadays, automation has been commonly seen as the integration of logical programmed software and various hardware devices [11] instead of a conventional hard-wired relay. Figure 7 demonstrates the advent of the automation concept along with the industrial revolutions. Industrial revolutions have been not only the most driven force but also an enormous provision of technologies for automation evolution via inventions and innovations come-up during revolutions. Electricity, electronics, digital computing and software, information and communication technologies, robotics, wired and wireless networks as well as Cyber-Physical systems, have completely transformed automation and its property.

As the automation technologies are rapidly advancing, nowadays automation has been applied widely in many aspects of lives. Regarding applications, automation is classified into 2 main types: home automation and industrial automation [11]. Home automation applies communication technologies and smart devices for intelligent controlling home or building appliances to increase the quality of modern living. The application aims to ensure safety, efficient control and eventually save the electric power consumption and human energy. Industrial automation, however, focuses on maximizing productivity, efficiency, and safety in industrial production processes. It is a large and complex encompassing of process, machinery [19], robotics, software, and information systems to keep a production and manufacturing process not only

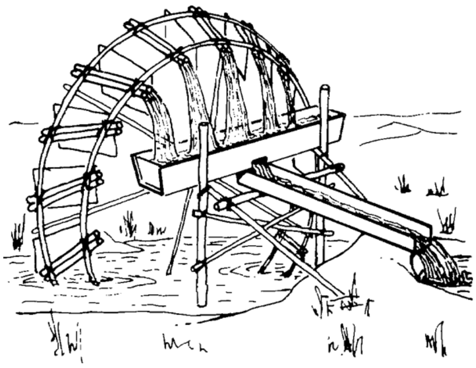


Figure 5: Noria waterwheel[14]

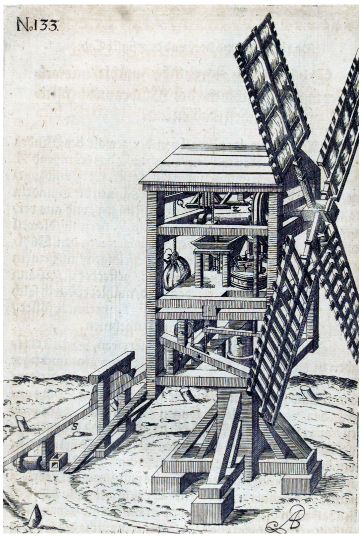


Figure 6: Post windmill with grinding machinery in mill housing, engraving from Agostino Ramelli's Li diverse et artificiose machine, 1588[17].

automatically but also smoothly, safely and consistently. In this thesis, aspects of industrial automation will be investigated to develop the production of BSF, therefore, understanding the advantages and disadvantages as well as determining existing types of industrial automation are important.

Automation integration to the industries results in intelligent manufacturing solutions for improved product quality and productivity with reduced downtime and wastes [11] leading to higher profit in production. Industrial automation also has been seen as a key factor in transforming a new concept of products to mass production and profitable business. According to [15], several main advantages achieved when applying automation in industries are:

- Replacing human operators in performing hard physical and monotonous work.
- Replacing human operators' tasks in dangerous environments.
- Obtaining tasks beyond human capabilities.

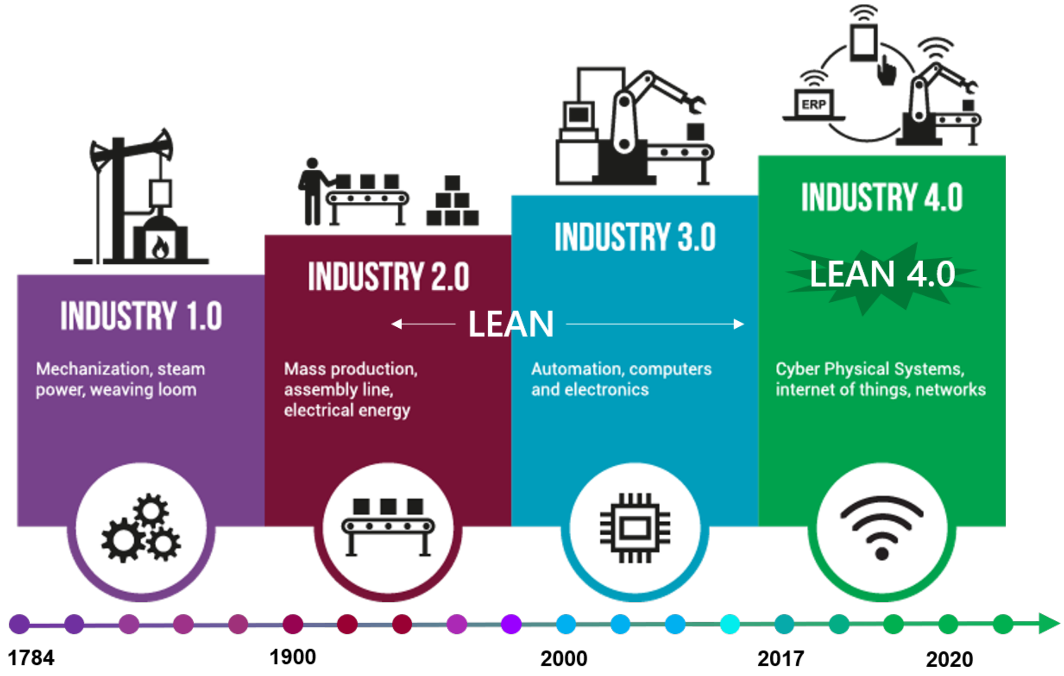


Figure 7: The advent of automation concept in the industrial revolutions [18].

- Increasing the speed of production
- Achieving high-quality control of products by automated checking system.
- Reducing the dependence on human availability.
- Providing opportunities for improvement in the economies of enterprises or society due to the relation between significant growth in business and massively growth in production.

However, few challenges have been raised for industrial automation. There still are remaining tasks that are unable [15] or not trivial to be automated. Also, the initial cost of investment is still high and in many cases, the use of humans is more cost-effective [20] than the automation approach. However, these challenges are gradually overcome with the exponential rise in computerization, information and network technologies as well as the reducing in equipment costs.

In [21] industrial automation is divided into two main types: process automation and factory automation. A similar classification is described in [22] but in different names: process automation and discrete/manufacturing automation. These classifications are based on the fields of industrial production: processing in plants and manufacturing in factories. According to [21], process automation is a continuous process and factory automation is an assembly process. In [22] it is explained more clearly that process automation is for processing raw materials to final products using physical and chemical changes and the final products can not be reversed to the raw materials. While discrete or manufacturing automation refers to automate assembly processes where different components are brought together to form the final products and the products can be reassembled into raw materials. There is a major difference in control techniques between these two types of industrial automation. According to [21], process automation is intensive in continuous control for monitoring and regulating factors of processing conditions such as temperature, pressure, level, and flow, thus analog signals are mainly used. Conversely, factory automation uses digital signals primarily as ON/OFF signals to operate machinery or assembly processes. Process automation is widely applied in petroleum, chemical and pulp, and paper. Factory automation is often used in automotive, logistics and electronics. In many industries, these two types are combined, such as food and beverage, cosmetic and so on. This classification helps the engineers to find the distinguished requirements of each application.

Based on integration level and flexibility, industrial automation systems are categorized into three basic types [23], [24]: fixed automation, programmable automation, and flexible automation. Figure 8 describes the relative positions of the three types of automation for different production volumes and product varieties.

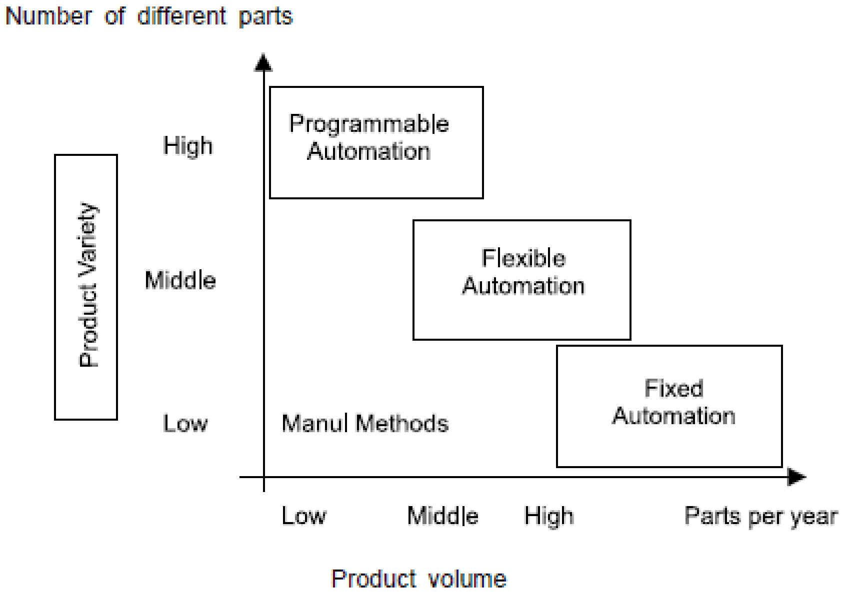


Figure 8: Relative position of the three different types of automation [23]

Fixed automation describes a system in which the sequence of processing or assembly operation is fixed by the configuration of equipment [23], [24]. It is commonly applied in systems that require mass volume and high production rate but a stable design of products [24] such as power plants or food production. In programmable automation, the processing or assembly operations can be changed by modifying the control programs of equipment [24] to accommodate different recipes or design of products. This type of system provides flexibility to deal with changes in products but requires a period of nonproductive time [25] for reprogramming and replacing tools. Therefore, it is more suitable for batch production. Robotics and CNC machines are good examples of this type. Flexible automation is designed to manufacture a variety of products [24] but the changeover of operations for different recipes is very quickly and does not interrupt the production [23]. However, this type of system requires a large initial investment [24]. It can be seen that programmable automation has the highest level of product variety but the lowest level of product volume. Fixed automation has a maximum capacity of production but a minimum of flexibility. In the middle zone, flexible automation can offer a system of medium product variety and produced volume.

3.2 Industrial automation essential elements

In this section, essential elements in an industrial automation system will be reviewed to apply for the development of BSF production automation. The presented elements include:

- controllers,
- actuators, motors, and drives,
- data acquisition and sensors,
- operator interface,
- industrial processes and automated machinery,
- material handling and robotics,
- control systems, and
- communication technologies.

3.2.1 Automation Controllers

To automate devices, machines or processes, controllers are used as the brain to handle collected information to make action-decisions. Controller devices in automation can compute the calculation of received data, generate control commands based on predefined instructions. The controlled targets can be an embedded device, a machine, a process or an entire plant.

Nowadays, there are numerous types of controllers from various vendors that are used for different purposes and are programmed by different languages and software. Lamb [15] has categorized into four common types of controllers: personal computers (PCs), programmable logic controllers (PLCs), distributed control systems (DCSs) and embedded controllers.

PCs not only have been used as a tool for business activities but also have been used as a controller in industrial control systems. The first attempts at using PCs for automation were often unreliable due to the stability issues of the operating system and failure rates of non-industrialized computers [26]. Nowadays, many manufacturers have released PCs for industrial purposes (IPCs) which are hardened by more stable operating systems and optimized the capability of real-time control.

The main benefits of using IPCs in automation control systems include: widely available [15], user-friendly interface [27], and possible to run the human-machine interface (HMI) application on the same machine with automation program [26].

PLCs are one of the most common controllers in automation industries. They are used in vast control applications such as machinery automating, process monitoring and manufacturing station control. PLCs are microprocessor-based that use programmable memory to store instructions or so-called control programs and implement functions such as logic, sequencing, timing, counting and arithmetic [19]. The control instructions can be programmed and modified easily then transferred to the PLC memory, which provides huge flexibility for adapting requirement changes. A basic structure of a PLC consists of a processor unit, memory, power supply unit, input/output (I/O) interface section, communication interface, and a programming device [19]. The processor continuously scans the condition of inputs, examines them with the programmed instruction stored in the memory then produces the response output signals within a bounded time [15]. This makes PLCs become a real-time system and have fast responses. With modular structure, extendible I/O interface, severe condition resistance and optimization for control tasks, PLCs are widespread in industrial control systems. Figure 9 presents PLCs from several manufacturers and Figure 10 demonstrates an example of the modular structure of a PLC from Siemen where CPU is central processor unit, DI, AI, DO, and AO are relatively digital and analog I/O modules, FM is function modules, and CP is communication processors.

Figure 9: PLCs from several vendors [28]

DCSs stand for a control system architecture, however, it also often referred to digital controllers that are connected and geographically distributed in such systems. They are often found in process control applications such as chemical and oil refining plants. DCSs are mainly used to treat analog signals and are originally a collection of PID controllers [21]. DCS controllers are developed for complex and advance control

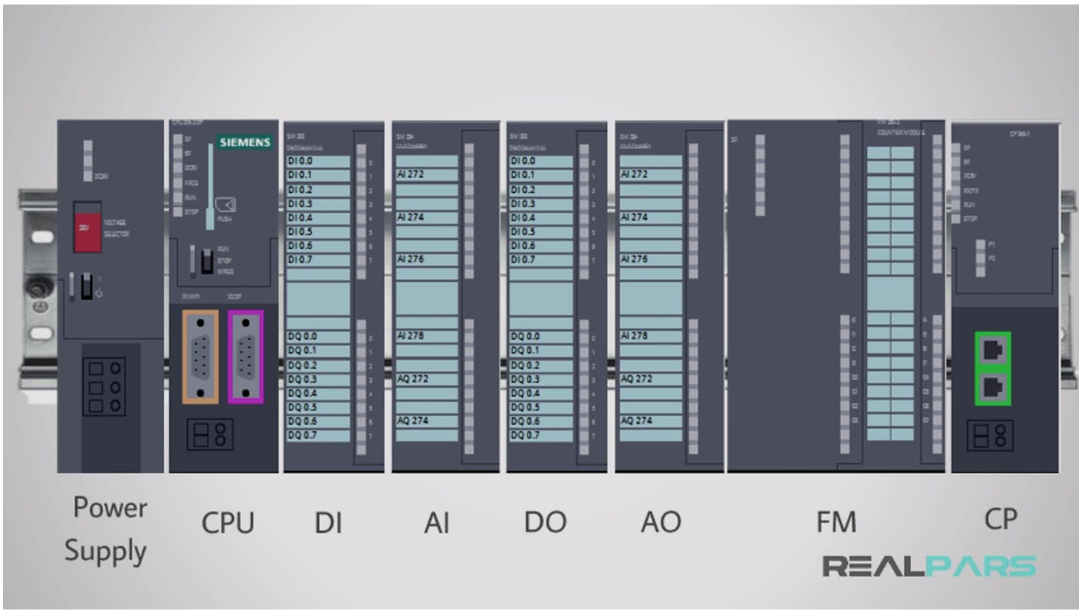


Figure 10: An example of the structure of a Siemen's PLC [30]

measures [29] which can handle many thousands of I/O points in a wide geographic area but still ensure high safety requirements and frequent adjustments. Control instructions of DCSs are designed to be configured by users in the form of function blocks which supports engineers to put fewer efforts into inter-communication in distributed systems [31]. Nowadays, DCS controllers are less expensive than before and are evolved to be used in discrete control applications as well.

Embedded controllers are control components that are embedded as a part in a complete device for performing one or a few dedicated functions [15] such as driving motors, adjusting temperature and processing signals. According to [32] embedded controllers are designed to help control power efficiency, maximize performance and are primarily used for controlling and monitoring machines in industrial automation applications. The common components of an embedded system consist of a microprocessor, memory, power supply and external interfaces that communicate with other parts of a larger system. Figure 11 shows an example of a temperature embedded controller which includes a display and keypad buttons to configure parameters.

Besides types of controllers above, programmable automation controllers (PACs) have been seen as a competitive solution to PLCs, DCSs, and IPCs in industrial applications. A PAC combines the functionality of a PLC and the processing capability of an IPC. Designed for large distributed control systems, PACs can operate in multiple domains simultaneously such as motion control, process control, sequential control, logic, data management, and communication using a single platform [33]. It can be said that PACs are the high-end level controllers, however, the decision of using them depends not only on application requirements but also on other factors such as cost, engineer previous experience, and local supports.

The numerous types of controllers available on the market have led to significant

Figure 11: An embedded temperature controller [34]

difficulties for engineers in choosing suitable ones for their applications. The differences between PLCs, PACs, DCSs, and IPCs are quite blurry due to the advance and competition among them and their vendors. However, many manufacturers have supported customers by giving several question guides such as the five steps to select the right controllers in industrial automation systems [35]. Several factors considered to help decide the right controllers are also discussed in [36] such as automation for new or existing systems, environmental issues, number, types and location of I/Os, communication technology requirements, and engineers' preferred programming languages and software.

3.2.2 Actuators, motors and drives

Actuators are one of the most important components in an automation system. Imagine an automation system as a human body, while the controller is the brain to execute thinking, decision making and generate commands the whole body, the structure of arms, legs and fingers can be seen as actuators to transform the commands into physical movements and action. In mechanization and automation, actuators are used to generate movement for internal or external components such as rotating a wheel and positioning a work-piece [15]. They convert an energy source into any type of motion, such as linear motion, rotational motion, and combination of both [37].

Nowadays, there are numerous of actuators used in machinery and industrial processes. However, based on the source of power, several common types have been widely used such as hydraulic actuators, pneumatic actuators, and electric actuators. Hydraulic actuators use the energy of liquid fluid such as oil to create a movement that generally produces very high force and pressure [15]. They often appeared in processes that required much force and pressure such as front-loader lifting and paper roller pressing. A typical example of a hydraulic actuator is a hydraulic cylinder. Another type is a pneumatic actuator that uses the fluid power of compressible air or inert gases [15] to generate motion. The advantage of pneumatic actuators compare to hydraulic ones is that the fluid of air does not require to be collected while the liquid fluid of hydraulic systems will cause contamination if it leaks out. However, with

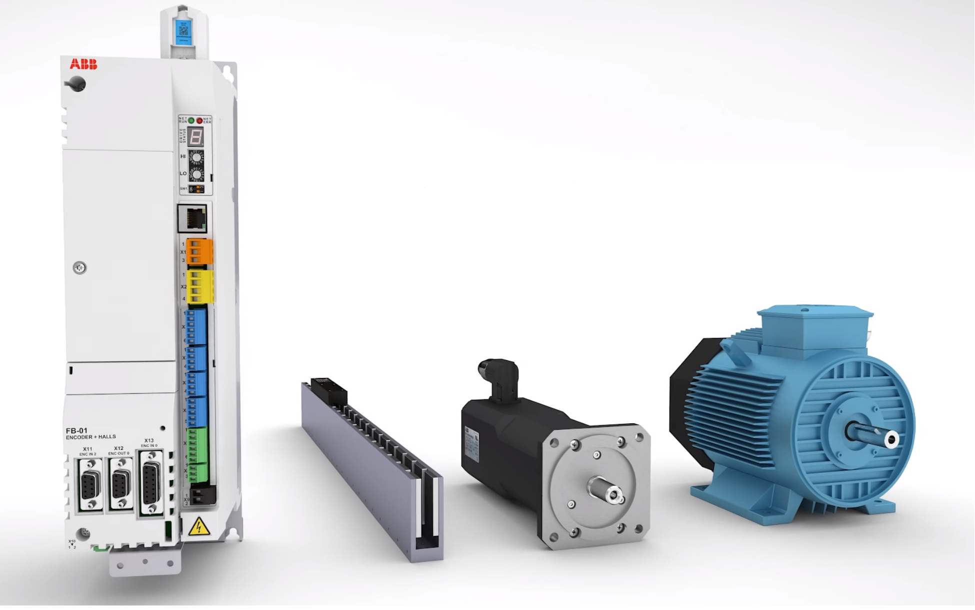


Figure 12: A picture of an AC motor, a servo and an electric linear actuator with a flexible drive (right to left) [41]

the same size, pneumatic actuators often generate less force than hydraulic ones [38]. The last main type is an electric actuator. Compared to hydraulic and pneumatic actuators, electric actuators recently have been seen widely used in many applications where compressed air and inert gases are not available, high force is not required but the precision of motion is intensive [15]. Electric actuators convert electricity into kinematic energy [39]. There are many types of them such as solenoids, motors, servomotors, stepper motors, electric linear actuators, and linear servos. While solenoid and motors are used for generating general motion like triggering levels or spinning fans, servo motors, stepper motors, electric linear actuators, and linear servos focus on precisely positioning such as manipulating robotic arms and CNC tools.

According to Lamb [15], [42], motor, servos, stepper motor and the proportional actuators which controlled by analog or digitally converted analog methods, often require controllers or drives or amplifier for motion control such as velocity, position, acceleration, and direction. In such motion control systems, the controller generates command signals for desired motion paths or trajectories and the drive or amplifier transforms the signals from the controller into higher power current or voltage to apply on actuators. Another important component in the systems is feedback devices which can be sensors, encoders, resolvers or hall devices. In different cases for various purposes, AC and DC motors do not require controllers or drives but motor starters and protective devices [43]. A common necessary device in using AC motors is the variable frequency drive (VFD). It is also often called as adjustable-frequency drive (AFD) which can generate various frequency and voltage to power AC motors from a constant frequency AC voltage [43], [15]. Figure 12 shows a picture of a drive that can be used for controlling AC motor, servo, and linear actuator.

3.2.3 Data acquisition and sensors

Data acquisition is the term used to describe devices that can capture data and information from the outer environment or the inner components to a system. According to [44], data acquisition devices are classified into two families based on their origin functions: detection and measurement. A detector detects a threshold or limit or estimates a physical measurement. A measurement device measures a physical characteristic to a given level of accuracy.

Various devices can perform the functions of measurement and detection, such as sensors, switches, and meters. In automation control, sensors have been widely used as feedback devices. Lamb [15] has explained sensors as devices that provide input to a control system and have divided sensors into two types: discrete sensors and analog sensors. According to the author, discrete sensors are used to signal the absence or presence of an object while analog sensors may sense physical qualities that can be described numerically. In this literature review, several typical sensors and data acquisition devices which can perform the most common functions, are summarized in Table 1 based on [15], [44].

Table 1: Common types of data acquisition devices and sensors

Function	**Device types**	**Captured data**	**Common application**
Object detection	Electromechanical limit switches	Physical contacts	Position controls for linear motion, simple avoiding collisions
	Inductive proximity detectors	Metal substance sensing	Metal work piece detection, detectors to control rotation
	Capacity proximity detectors	Conductive and isolating substance sensing	Non-metal work piece detection
	Photoelectric detectors	Light changes	Varying type of object detection
	Ultrasonic detectors	Sound pulses changes	Varying types of object detection, tank level controls
Physical measurement	Temperature sensors	Temperature level	Temperature limit safety, temperature meters
	Pressure sensors	Pressure level	Pressure limit safety, pressure meters
	Flow sensors	Flow level	Low limit safety, flow meters
Special purposes	Bar code reader	Mapping of patterns	Good information traceability, warehouse management
	RFID reader and tags	Data in form of radio frequency signals	Good traceability and tracking, warehouse management
	Encoders and resolvers	Positions or directions	Position, speed, acceleration or direction control for actuators
	Vision sensors	Image characteristics	Good detection, good quality control, human action detection

3.2.4 Operator interface

To control machines and to monitor conditions of processes, an operator must provide the command signals and receive the status feedback from a system via an operator interface. Early operator interfaces were simply in the form of control panels with pushbuttons, switches, pilot lights and meters [45], [15]. With the advance in electronics, digital computing, and other technologies, operator interfaces have been evolved to integrated graphic display, text and touch screens. Not only involved in appearance and hardware components, but operator interfaces also have been blended with advanced functions such as fault detection and alarming, process visualization, data handling, and parameter configuration. There are many types and forms of operator interface commonly used in industries such as man-machine interface (MMI), human-machine interface (HMI), graphical user interface (GUI) and operator interface terminal (OIT) [15].

In industrial automation, HMI has been seen as the most commonly used term. HMIs are devices that provide the physical interaction between humans and machines or processes. They can be integrated with controllers such as PLCs, DCSs or can be separated dedicated devices. HMI solutions were categorized into four main types in [44], including: binary control and indication operator interfaces, compact terminals, graphic screen terminals, and industrial PCs associated with HMI and supervision software. Binary control and indication interfaces present states and binary control. These states and binary control are performed by simple components such as pushbuttons, selector switches, LEDs, counters, color display and so on. The document has suggested that this type of HMI is ideal when the amount of information exchanged between operators and machines is low and limited to binary control. Compact terminals, also called as alphanumerical or matrix terminals and displays, provide more advance dialogue with alphanumerical and semi-graphic characters. These types of HMI are connected to a central processing unit by communication buses and are often used for the individual operation of machines. Graphic screen terminals are described by their provision of enriched and user-friendly graphical functions such as graphic display, alarm processing, application setting, diagnostics, maintenance and so on which can be displayed by text, images, and graphs on a screen. The document has claimed that this type of HMI is applied for machines controlled by PLCs. Lastly, industrial PCs associated with HMI and supervision software provide various functions with information flows among machines, operators and management levels by using the Ethernet standard in the industry. The HMIs are run on industrial PCs and can be achieved by various software. This type of HMI solution can be used to help operators to supervise, control and manage the operation of a production line or a distributed automation production system. Figure 13 demonstrate a different solution of HMIs used in industrial automation.

The selection of solutions for operator interfaces or HMIs can be considered based on several criteria such as required functions, control system architectures, the volume of the flow of information, types of communication interface with other systems [44], level of security, costs and so on. A selection guide is presented in [46] based on the three primary roles of an HMI that are desired from operators: a pushbutton

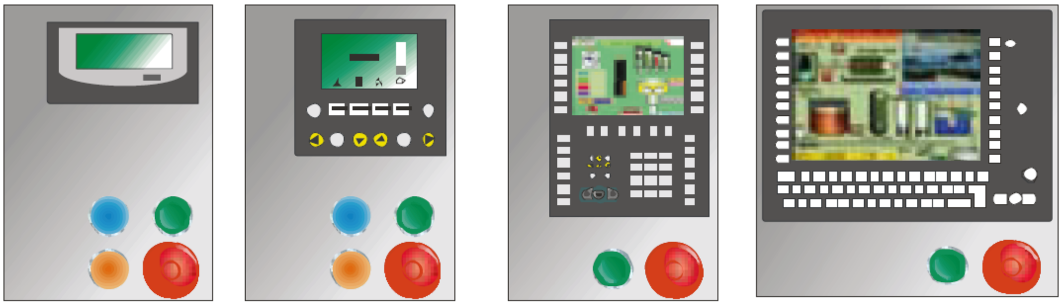


Figure 13: Different types of HMIs described by Schneider Electric [44]. From left are a binary control and indication operator interface, a compact terminal, a graphic screen terminal and an industrial PCs associated with HMI and supervision software

replacer, data handler, and overseer. For a pushbutton replacer, an HMI with an LCD screen can be used. Data handler HMIs would need large memories and user-friendly interface. Overseer HMIs are used for monitoring and controlling complex large systems and usually links to database systems and software programs. Therefore, they are most likely required to run Windows and have a luxury communication interface such as Ethernet ports.

3.2.5 Industrial processes and automated machinery

In the production and manufacturing industries, there are many processes to handle materials physically and chemically. The processes can be semi-automated or fully automated by machines and equipment. In this section, size reduction, mixing and drying processes are studied with several types of automated machines.

Size reduction is the process of turning bulk material into smaller size particles [47]. As many processes depend on the size and shape of materials, this type of process appears in many industries such as food and feed production, waste processing and pharmaceuticals. According to [48], size reduction may be obtained by two methods: precipitation and mechanical process. Precipitation uses an appropriate solvent to dissolve substance and a mechanical method uses force and pressure to break materials. Mechanical methods are widely used with many techniques available such as crushing, grinding, fine grinding and cutting [49]. Several common industrial machines are shredders, hammer mills, roller mills, and lump breakers. Figure 14 illustrates the structure of a pneumatic discharge hammer mill which is ideal for wood scrap milling and Figure 15 shows an example of industrial shredder which are ideal for bulk waste size reduction.

In order to select a suitable solution, it is essential to investigate the properties of raw materials such as input size and shape, hardness, abrasiveness, bulk density, moisture content and so on [52]. Besides, the desired final size of products is also important when selecting the relevant machines. In [53], a five questions guide is suggested to obtain the most relevant solution for a process. The questions are about raw materials properties, desired output particle size, and production rate. The information should be provided to the suppliers when selecting a size reduction

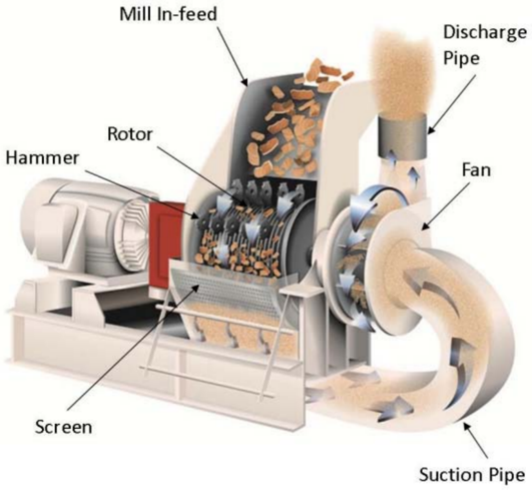


Figure 14: Structure of a pneumatic discharge hammer mill [50].

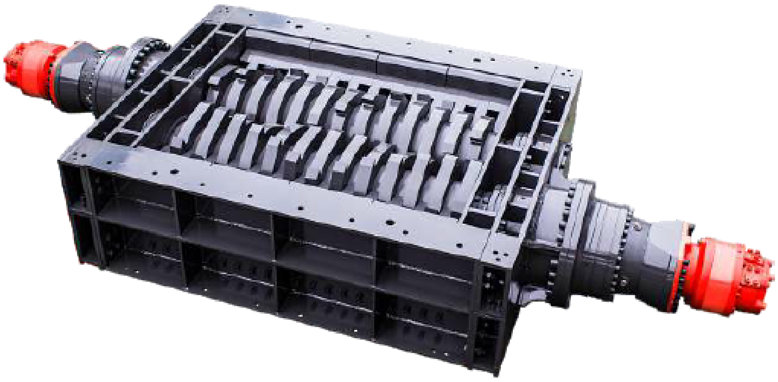


Figure 15: Picture of an industrial shredder [51].

system.

Mixing is another common process applied in many process industries such as food and beverage, pulp and paper, pharmaceuticals, and cosmetics. Mixing has been defined as the process of thoroughly combining different materials to produce a homogeneous mixture [54]. In many processes, the quality of final products depends on the consistency of the raw materials such as the same proportion of compositions [55], uniformed particle size distribution, consistent moisture content, color, texture, and other required attributes [54]. For example, in bakery, well-mixed ingredients of flour, eggs, milk, sugar, oil, and water will produce bread with proper texture, good appearance, and consistent taste. In industrial processes, mixing is applied to various types of materials such as liquid, solids, gases, and pastes [54]. Therefore, there are many types of mixers for different materials and different purposes of processes. According to [56], industrial mixing machines are mainly divided into four categories:

blenders, agitators, heavy-duty mixers and portable industrial mixers. Blenders are mixers made for blending bulk solids with other solids such as ribbon blenders and tumbler blenders. Agitators are mixers for mixing fluids with other fluids, dispersing gases into liquids, heat transfer and suspension of solids in liquids. Heavy-duty mixers refer to machines used for mixing viscous, paste-type and variable viscosity materials. Lastly, portable industrial mixers are motorized impellers which can be movable to mix material in different containers such as tanks and drum containers and are often used in coating applications. There are also other classifications of mixers based on operation continuity as batch or continuous mixing [57]. To select a suitable mixing machine and equipment, it is recommended to consider several factors when asking for a solution from vendors such as the size of the container, mixing capacity, material properties and desired results [56]. Figure 16 is a picture of a ribbon mixer used in industrial applications.

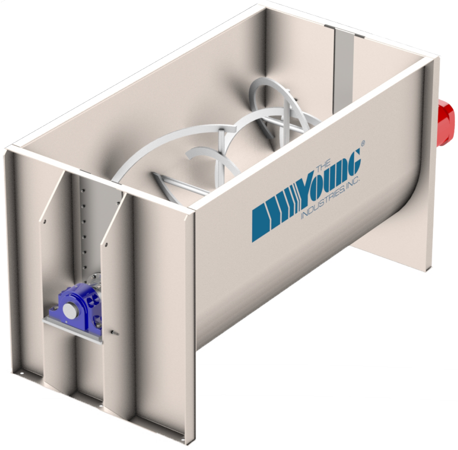


Figure 16: Horizontal ribbon mixer [58].

Figure 17: A belt dryer which can be adapted to direct and indirect heating [59].

Drying is another important operation in industrial processes. It is described as the process of thermally removing moisture [60] from a solid substance. In this process, heat is supplied to contact the wet solid substance in a period of time leading the evaporation of liquid [61], [60]. Drying is an essential operation in many industries such as chemistry, food, ceramics, pulp and paper, feedstock, and pharmaceutical. The purposes of the process are to refine the final products, to obtain free-flowing materials, to preserve and store products or to reduce the cost and difficulty of transportation [60]. Drying technologies have evolved and become more diverse and complex [62]. Drying has been claimed as the oldest and most common chemical engineering unit operation with over 400 reported types of dryers and over 100 common available distinct types [60]. In the industry, typical classification of dryers is based on the mode of operation as batch or continuous and based on the mechanism of heat transfer as direct, indirect, radiant and microwave [62]. According to [62], direct dryers use heat transfer medium (steam, hot gases, thermal fluids and so on) to contact the wet materials. This type has known as the most common type of industrial dryer. Indirect dryers supply the heat to the wet materials without direct contact of drying medium but via conduction. Radiant and microwave dryers use radiation to supply heat to the wet materials. Radiant and microwave dryers have been considered expensive in energy costs but beneficial for heat-sensitive materials [62]. These types of heat transfer mechanisms can also be combined. It is understandable that selecting suitable machines and systems is not trivial. However, many vendors have provided their solutions in some range of applications which can be used as a reference for customers. And most of drying machines and systems can be custom made to obtain specific requirements. Several crucial factors for selecting suitable dryers have been discussed in [62] such as drying throughput, wet material properties, desired moisture content of product and processing operations. Figure 17 show an example of industrial drying machine which can be adapted to direct and indirect heating method.

3.2.6 Material handling and robotics

Material handling is defined as the operation involving the movement and storage of materials within a facility or at a site [63]. Equipment, machines, and systems for material handling are diverse and can be classified based on the nature and types of works into several categories: transporting, positioning, unit load forming, storing, and identifying and controlling equipment [63], [27].

Transporting equipment refers to devices and machines which are used to move materials between processes, production stations or facilities. In this category, the main types of equipment are conveyors, industrial trucks, and cranes [63]. The selection of these different types of transporting solutions is influenced by several main factors such as the characteristic of the materials, transported quantities, transporting distance and also costs [27]. For example, to frequently transfer small size and lightweight of assembly parts between stations in a production line, conveyors can be seen as the most optimal solution rather than trucks or cranes. However, for transporting of bulk and very heavy parts between a warehouse and production sites, trucks, automated guided vehicles (AVGs) and even crane may be considered as better options. Conveyors have a diverse type with numerous designs and multiple variations such as belt conveyors, roller conveyors, crew conveyors, bucket conveyors, and chain conveyors. Each type is only suitable for several types of materials, therefore, it is possible to select a suitable solution if the characteristics of conveyed materials are thoroughly examined.

Positioning equipment is used at a single location to locate materials into correct positions [63]. This type of machine and equipment can be lifting or rotary tables, feeders or hoppers, palletizing mechanism or industrial robots. Lifting, rotary or similar types of tables are commonly used in assembly and manufacturing stations to adjust the height or direction of materials at the desired position and orientation. Feeders and hoppers are often seen in process machinery and equipment which acts as the connections between machines and conveyors to guide the flow of materials. Palletizing mechanism and palletizing robots are used to organize workpieces on pallets or in containers which support the transporting operations.

Unit load formation equipment is used to restrict materials to be maintained their integrity [63]. Examples of these types are boxes, bins, baskets, crates, bags, and bulk load containers. These equipment make the positioning, transporting and storing of materials feasible and effective. As many types of equipment will contact directly to the materials, therefore, it is important to consider the impacts of contained materials on the contact surface of the equipment.

Storing equipment is used for holding and buffering materials over a period of time [63]. This type often refers to the facilities of warehouse systems such as storage floors, shelves, and racking systems. In the industrial warehouse, in order to store as many materials as possible, several racking systems are used beside on-floor facilities. Base on specific requirements of space, form of stored materials, methods of transporting, volume of storing, automated level and investment costs, there are several types of racking systems available in the market such as selective racking, drive-through racking, drive-in racking, push-back racking, satellite racking, mobile racking, and automated storage and retrieval systems [64].

Identification and control equipment is responsible for collecting and monitoring the information of material flows within a facility as such within a factory or a warehouse [63]. Several technologies have been used widely in industrial logistics such as bar codes, RFID tags, machine vision and so on. The handled information of material flows consists of types of materials, dates of transportation and production, locations or ordering information.

Industrial robotics have been used widely and have been seen as a trend in industrial production. According to [15], ISO 8373 has defined an industrial robot as an "automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes". The definition has extended in [65] by emphasizing the flexibility of industrial robots that industrial robots can be equipped with different end-effectors for industrial applications. Indeed, industrial robots are flexible and adaptable to various tasks in manufacturing processes such as welding, material handling, packaging, pick and place and so on. It is possible that with the same robot, it can handle these different tasks just by changing the end tools like changing grippers or replacing the gripper with a working tool. The need for robotics in industrial is to replace or support humans on four tasks required automation, augmentation, autonomy, and assistance in four types of working environment: dangerous, dirty, difficult and dull environments [65].

There are several types of industrial automation such as articulated robots, Selective Compliant Assembly Robot Arm (SCARA), and Cartesian coordinate robots. An articulated robot has been described as a chain arrangement of rotary joints [15]. Each joint is connected to another joint by rigid links [65] which resemble a humans arm [66]. As resembling the flexibility of human arms and requiring least floor space [66], articulated robots have been seen as the most common in industrial robotic applications. Another common type is called as SCARA. It is the acronym of Selective Compliant Assembly Robot Arm or Selective Compliant Articulated Robot Arm [15]. SCARA robots have more than one type of motion of axes: rotation and translation. While articulated robots use rotary joints to connect links, SCARAs combine rotary joints with prismatic joints [65] by several linear actuators. A typical SCARA robot consists of two rotary shafts positioned vertically and a horizontally movable end-effector [66]. This structure provides compliance in one selected plane [66] that is ideal for assembly which requires rigidity in the X-Y plane [15]. Another robot type is a Cartesian robot that has a structure of three prismatic joints to provide linear motion on three axes X, Y, and Z according to Cartesian coordinates [66]. This design provides high position accuracy with simple operation and easy programming [66].

3.2.7 Industrial automation control systems

A control system organizes the controllers and field devices into a system to obtain automated control. This section will present the three common types of control systems in industrial automation: Supervisory control and Data Acquisition (SCADA), DCS and PLC systems.

According to [19], SCADA is a computer-based system to monitor and remotely control processes. A typical SCADA system consists of four components: a central computer, remote terminal units (RTUs), a wide-area communication system and an operator interface. RTUs are responsible for collecting data from field devices and receiving control demand signals from the central computer. A SCADA software runs the central computer to gather the collected data from RTUs, presents the data via a graphical interface to operators and generates control commands to RTUs. PLCs can also be integrated to a modern SCADA system [67], [68], [69]. The reason was explained in [67] that PLC offers a standard hardware solution at an economical price. Figure 18 shows a diagram of a typical SCADA system where a PLC replaces the need for a central computer and the SCADA software is accessed via operators' computers.

DCS systems also comprise the data acquisition and control functions, however, the functions are performed by a number of distributed microprocessor-based units located near to field devices [67]. Each DCS controller controls the field devices of its own and maintains the communication with other controllers. Operating PCs then monitor all the DCS controllers through a high-speed communication network [70]. For applications, DCS systems are designed to control complex and

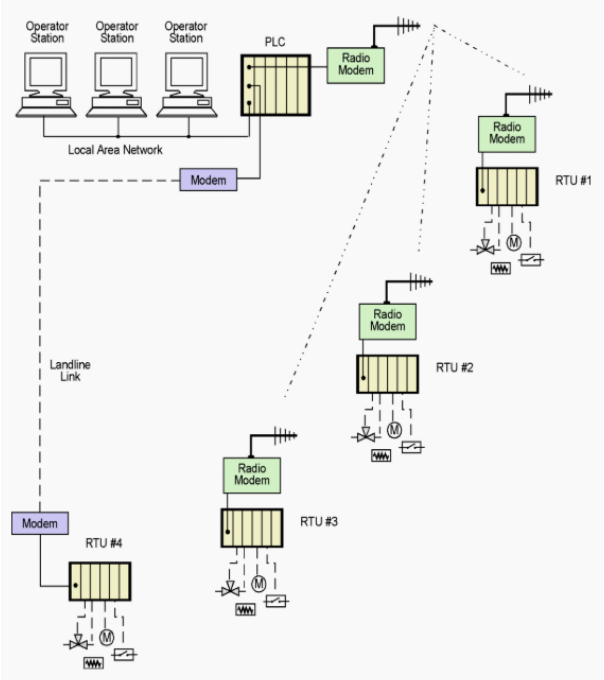


Figure 18: A diagram of a typical SCADA system [67].

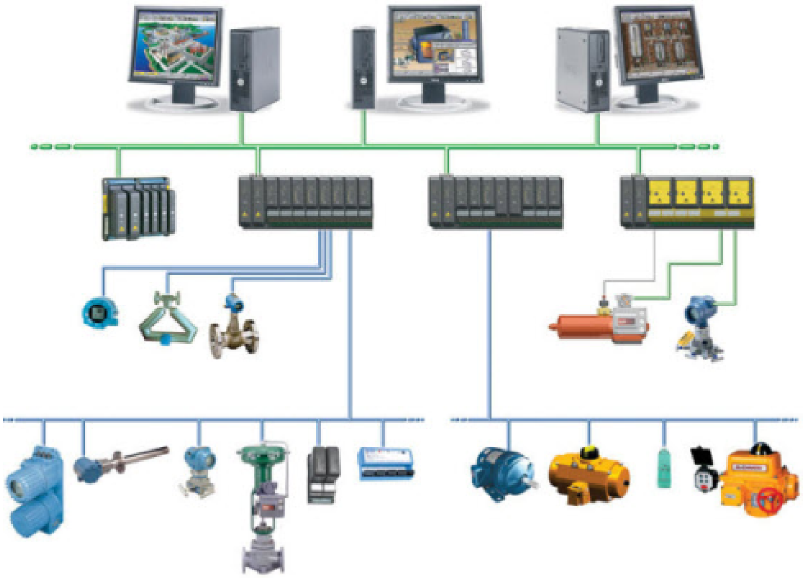


Figure 19: An example of a DCS system [70].

geographically distributed applications such as large chemical processes [15], [70]. Figure 19 demonstrates an example of a DCS system.

Since PLCs are hardware controllers without any HMI, a PLC control system often requires to be integrated with HMI applications or SCADA software on PCs [69]. In this type of system, a PLC controls the whole system, while HMI and SCADA software provides interface for operators. According to [69], PLC/HMI systems are often used to locally control machines and small processes while PLC/SCADA is used to remotely monitoring processes. In modern systems, the combination of SCADA software and distributed PLCs has provided PLC systems features similar to DCS systems. While DCS systems are less expensive than before which makes it suitable to be used in the discrete manufacturing process as well. Therefore, PLC systems and DCS systems can be seen as competitors to each other in many industries.

3.2.8 Industrial communication

Communication plays an important role in industrial automation. Without communication, it is impossible to transfer information to establish control networks among devices, machines, and operators. This section will briefly review several communication technologies widely used in industrial automation, including: I/O interface, serial communication, Ethernet, Fieldbus, wireless and Open Platform Communication Unified Architecture (OPC UA).

Digital and analog I/O wiring are the most simple interface to connect peripheral devices to controllers. Digital I/Os use low-voltage and current signals to transmit discrete signals [15]. Depending on applications, different electrical signals are used such as 3.3 VDC, 5 VDC, 8 VDC, 24 VDC, and 120 VDC [15]. A controller uses digital I/Os to monitor the status of discrete sensors, switches, contacts or to drive control of lamps, relays or actuators [71]. In contrast, analog I/Os use electrical current or voltage to represent continuous signals [73]. The common standard analog ranges in industrial automation are 0 to 20 mA or 4 to 20 mA for current or 0 VDC to 10 VDC for voltage [15]. Controllers use analog I/Os to measure data from analog sensors such as temperature and pressure sensors as well as to regulate the position or speed of an actuator.

Serial communication transmits strings of 1s and 0s to send and receive data over one or two lines [15]. An advantage of serial communication is its few signal wires which allow serial communication interface to save wiring materials and relaying equipment cost [74]. RS-232 has been used widely between computer terminals and various manufacturers' control platforms [15]. Other common serial communication standards are RS-422 and RS-485. These two standards have much longer cabling distance than RS-232 which can reach up to 1200 m of cable connection [74].

Ethernet is a communication standard for computer networking in a local area network (LAN) [75], [15]. The network is to connect multiple devices such as computers and control devices so that they can share information in a location. Ethernet uses coaxial cable, twisted pair, and fiber optic as the medium to transmit data [75]. These cable types have standard physical connectors that allow simple and easy connections to devices. Ethernet provides a high speed and large data volume of transmission. Depending on application requirements and costs, the speed of Ethernet can range from 10 Mbps to 10 Gbps [75]. In industry, Ethernet has been widely used as a communication medium for various industrial protocols such as Ethernet/IP, Modbus/TCP, Profinet and EtherCAT [15], [76]. To take advances of the Ethernet's benefits, the protocols haven developed by many manufacturers or groups of manufacturers for their own devices and for specific fields. A suitable protocol can be selected for an industrial Ethernet based on the requirements of applications and the compatibility of equipment.

Fieldbus has been defined as a group of industrial computer networking protocols developed for distributed control in real-time [15], [77]. It provides a communication network for field devices and controllers which requires only one communication point at the controller level to connect hundreds of analog and digital nodes [77] along a single wire pair [19]. Therefore, Fieldbus reduces the use of wired cables and simplify the floor wiring. There are several protocols in the Fieldbus group such as ControlNet, Modbus, Profibus, EtherCAT, HART, and AS-i. Depending on the compatibility of devices from the vendors, suitable protocols can be chosen to establish a Fieldbus network.

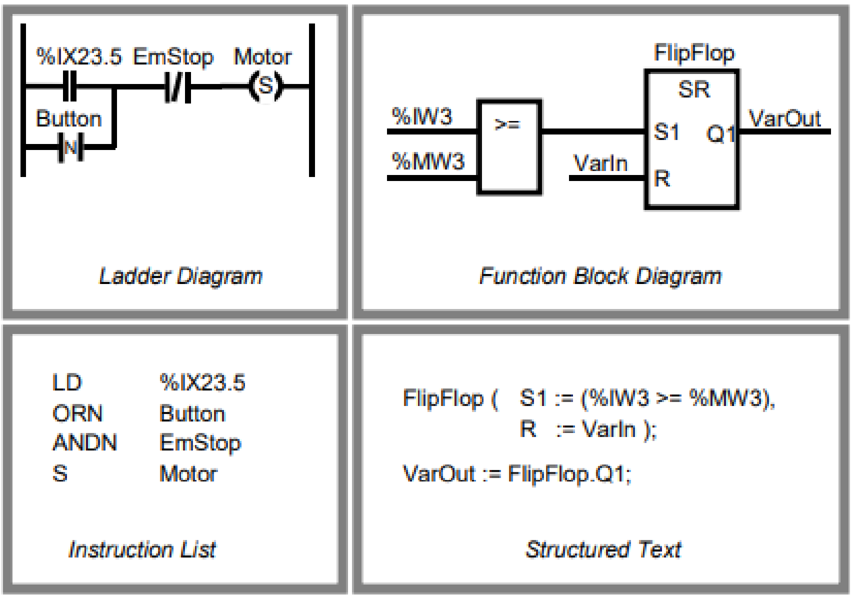
Wireless communication refers to the transfer of information between devices over a distance without wired connections [76]. The major advantages of wireless include the eliminating of physical wiring and the ability to extend connection points [77]. Wireless networking is increasingly forcing industries to switch from wired to wireless networks. A wireless local area network (WLAN) is a network of wireless communication that connects multiple devices in a location [15]. In such networks, Access Points (APs) connect wireless devices to a wired Ethernet LAN network [76]. Within the coverage area of APs, the devices can be moved freely and still remain connected to the network. Wi-Fi is a WLAN using IEEE 802.11 standards [15]. It is one of the most common wireless technologies used in industrial automation applications such as AGVs systems. Other wireless technologies are also widely used such as Bluetooth, Cellular, WirelessHART, and ZigBee.

OPC UA is a communication technology developed from OPC (object linking and embedding for process control) which defines a standard for the secure and reliable exchange of data among devices from multiple vendors in industrial automation [78]. According to [19], OPC UA unified all specifications of OPC into an open platform that supports many operating systems and embedded systems. OPC specifications define the interface between clients and servers, as well as servers and servers to implement the data exchange for three types of data: real-time data, alarm and events and historical data access. OPC servers are responsible to read data from devices or to write data to devices while OPC clients are to access data from the servers. These specifications are combined by OPC UA so that the data can be accessed by using a single server interface. Since OPC UA is a communication standard among devices from multiple vendors, it is often used as an integration method to connect devices from different vendors.

3.2.9 Automation software

Automation software is vital in modern industrial automation. The automation software is programmed to provide predefined instructions for the hardware controllers to generate control commands. Two main programming standards widely used in the industrial automation are IEC 61131-3 and IEC 61499. In this section, a brief overview of these two programming standards is provided.

According to [15] and [80], IEC 61131-3 is an open international standard for PLCs which has three graphical and two textual programming languages. The graphical languages are ladder diagram (LD), function block diagram (FBD), and sequential function chart (SFC). The textual languages consists of instruction list (IL) and structured text (ST). LD is based on the graphical representation of coils and contacts to indicate Boolean logic operations. FBD uses boxes and lines to express the connection of arithmetic, Boolean or other function elements and function blocks. SFC display sequential and parallel execution of the program using steps, links and transitions. For the text-based language, IL is a low-level language similar to machine code while ST is defined as a high-level one. Figure 20 demonstrates an example of the programming language of IEC 61131-3 standard.



```
LD      %IX23.5
ORN     Button
ANDN    EmStop
S       Motor
```

```
FlipFlop (  S1 := (%IW3 >= %MW3),
            R  := VarIn );

VarOut := FlipFlop.Q1;
```

Figure 20: An example of IEC 61131-3 standard's language [80].

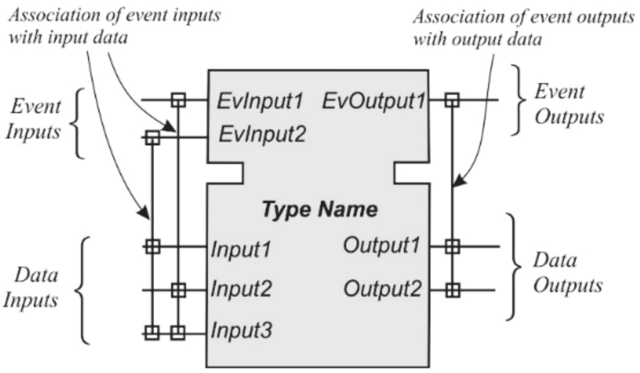


Figure 21: IEC 61499 standard's function block interface [81].

IEC 61499 is another approach to design automation control program. According to [81], IEC 61499 uses function blocks to define a component-based modeling approach which simplifies the design of distributed controllers. Figure 21 describes the interface of an IEC 61499 standard's function block. An IEC 61499 function block consists of two main part: event variables in the ”head” and data variables located in the ”body”. Event variables are used to pass information about events from one function block to another while the value of data variables associated for each event defines the transferred information. The function blocks can be created by users in a software tool by providing the definition of events, data and the association between them. Once a function block is developed, it can be stored in library and can be reused in applications.

4 Development

After reviewing the literature on BSF and industrial automation, a six-step strategy is implemented for the development of BSF production automation. The five steps include:

1. determining the requirements and specifications for the production,
2. calculating desired capacity of processes,
3. selecting machinery,
4. designing automated operations for BSF processes,
5. proposing a method of machinery integration, and
6. designing state machines for automation control.

The requirements and specifications of the BSF production are described in Section 4.1. Section 4.2 and Section 4.3 provide the implementation of capacity calculation and machinery selection for the main processes of the production. After achieving a collection of machines, automated processes are designed in Section 4.4. Section 4.5 presents the integration method of selected machinery. Finally, the designing of state machines for automation control is described in Section 4.6.

4.1 Requirements and specifications determination

4.1.1 Production requirements

While many facilities have been built for BSF rearing, they have been seen as labor-intensive and difficult to be industrialized. Consequently, it leads to a limit biowaste processing capacity, produced volume and inconsistent quality of BSF larvae. Therefore, the main objectives of the development are to design an automated production process which reduces significantly the dependence on manual tasks and increasing the capacity of production. This section will present the requirements for the production of BSF, including required raw materials, desired final products, operations of the production process as well as several performance requirements.

The main raw material of the production is biowaste or organic by-products such as fish by-products and food processing by-products. The raw material is selected according to the available sources in the local, however, the quality is fairly constant. The desired final products are dried larvae, extracted oil, and frass. Based on the manual production process described in Section 2.2, the production was defined into five main sub-processes or processing units: 5-DOL reproduction, biowaste re-processing, rearing unit handling, warehouse rearing and post-processing of products. Each sub-process has its own handled materials and desired production operations which are presented in Figure 22. The 5-DOL production unit and its input materials are blurred to indicate that they are not considered to be included in the development. As 5-DOL production evolves complex tasks such as capturing flies for mating, collecting eggs, and harvesting hatched larvae, it may require to designed complicated systems to automate the tasks. Besides, this thesis has a small scale of production that desires a small amount of 5-DOL. Therefore, it is sensible to keep producing 5-DOL by hands and keep it as an external process of the BSF larvae production.

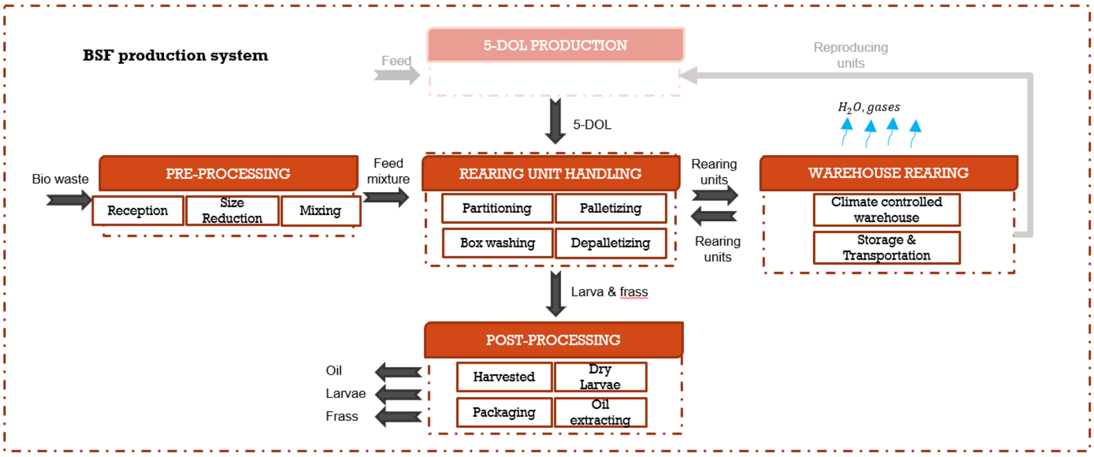


Figure 22: The BSF production system

Biowaste pre-processing unit is responsible to receive and pre-treatment the raw material. The raw material is assumed that the quality is controlled at the sources. Several hazardous materials and inorganic substances such as metal pieces, glass or plastic bags are ensured to be sorted out before entering the facility. However, the pre-processing unit should be able to operate stably in case some pieces of these materials are accidentally left out in the waste. After received at the reception, the waste will be transferred to the pre-treatment section. The pre-treatment section involves a reduction of waste particle size and a blending or mixing of waste to create a relatively homogeneous feed mixture for the larvae. The size of the waste particle and the level of the homogeneous mixture are required to in certain range because they will impact directly to the quality of the final product.

To increase the rearing capacity in a space-saving and easy transporting manner as well as to improve the quality control of rearing, BSF larvae are fed in small containers so-called rearing units. In the rearing unit handling process, the feed mixture is partitioned into the rearing units with an amount of 5-DOL. Partitioned rearing units are then stacked on pallets for transporting to the rearing warehouse. After harvested from the warehouse, old rearing units are unloaded from pallets for the next process. Another requirement is that the dirty boxes are desired to be cleaned after harvesting. Figure 23 shows an E1 plastic box which is used as a rearing container.

The warehouse for storing rearing units is a closed area that is desired to be able to maintain the ideal environmental conditions for the growth of larvae. As mentioned in Section 2.1, the optimal conditions include warm climate, shaded area, and controllable humidity. If the climate is too cold, the larvae will slow down the development. If it too hot, they will escape from the containers. Besides,

Figure 23: Image of a BSF rearing box [79].

implementing good ventilation in the warehouse is a key factor. Dynamic airflow will avoid moisture-saturated air and maintain the sufficiency of oxygen for larvae growth. Another desired operation of the warehouse is storing capability. The warehouse has to receive and retrieve a number of rearing units daily and to be able to store them during the larval development.

After harvested from the warehouse, rearing units are transferred to the post-processing unit for further refining. Frass is separated from larvae and transferred to outside storage. Before entering the separation process, the harvested substance should be crumbly with low moisture for easy sieving. After separated from the residue, larvae then will be killed and dried to remove moisture. The process after drying is extracting larvae oil from larvae protein. Larvae oil then can be stored in bulk tote containers and larvae protein is packaged in bulk bags.

4.1.2 Process specifications

After summarizing the requirements of the production, the specifications of each processing unit were collected for the development. The specifications were used to select machinery and to design the automated operations for the processes. Figure 24 illustrates the specifications of each process which were summarized from Section 2.2 as well as collected from personal discussion with experienced people in practice.

The pre-processing unit has specifications of prepared larvae feed. As can be seen from the figure, the particle size of biowaste is required to be less than 20 mm in diameter. Since the BSF larvae have no chewing mouthparts, big particles may decelerate the digesting of larvae. This results in bad larvae growth and causes difficulty in the separation of harvested substance due to undigested chunks. Another factor influences the growth of larvae is the moisture of waste mixture. The water content level of the mixture should be between 70% and 90%. To maintain balance rearing among units, it is also desired to ensure the mixture having a good distribution of moisture.

The rearing unit handling system has four main functionalities: partitioning feed mixture and 5-DOL into boxes, loading new rearing units onto pallets, unloading units from harvested pallets, and washing harvested boxes. The container unit has a dimension of 60 cm length, 40 cm width, and 12.5 cm height. Since the height of pallets is targeted at about 120 cm for standard, eighteen units can be stacked

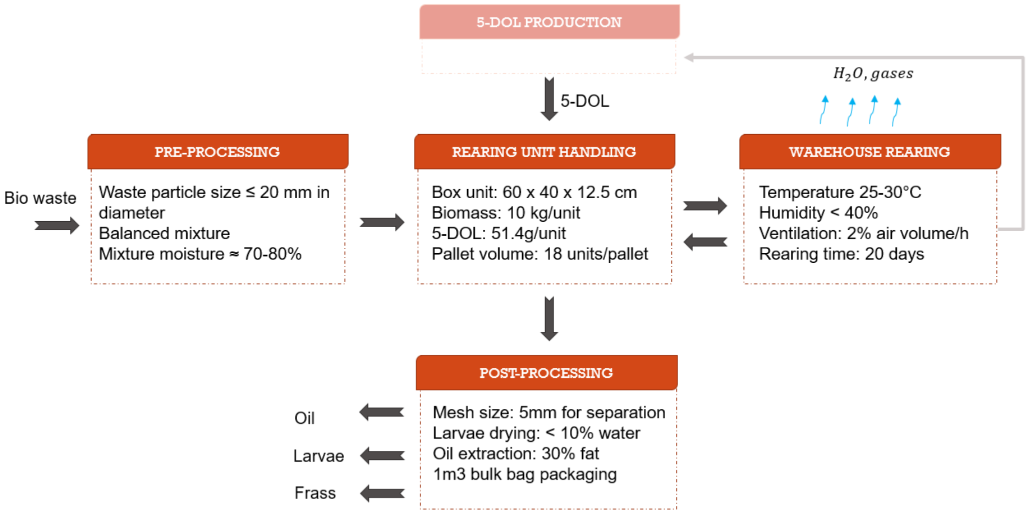


Figure 24: Specifications of production processes

together on a pallet so that it has two units on a layer. In this project, the haft-pallet type is selected because two boxes organized on a layer provides three sides of boxes available for aeration.

New pallets of rearing will be stored in an optimal conditional warehouse for the growth of larvae. The warm climate is defined as the temperature ranging between 25 °C and 30 °C. The humidity of the environment is required to maintain no greater than 40%. For better quality control of rearing, the climate should be controllable and the data of the environment should be recorded for further research and development. Moreover, ventilation of the warehouse should be has a capacity of 2% of total air volume per hour. This is optimal to replace the moisture and emitted gases as well as to provide sufficient oxygen for the well-being of larvae. In addition, the warehouse has to be able to store a number of pallets in twenty days of rearing plus several slots for preventive.

In the post-processing unit, the specifications are for product separation and larvae refining processes. Sieving methods have an optimal mesh size of 5mm. The residue falls through the mesh and the larvae remain against the mesh threshold. For further refining, the harvested larvae should be dried to ensure the water content less than 10%. As the larvae contain about 30% fat, the oil is extracted from dried larvae to obtain the concentrated protein and to avoid the rancid oil during preservation. Extracted oil can be filled into containers and the larvae protein is packed in one cubic bulk bag.

4.2 Process capacity calculation

The capacity and throughput calculation were executed to define the required processing capability of each sub-process. The structure design and component selection of developed processes were implemented based on the desired functions and required capacity. In the calculation, capacity referred to the maximum amount of material that a process handled in a period of time. The capacity was also used to indicate the total amount of material that a machine or a facility could contain.

The calculation was executed by using the desired annual processing capacity of biowaste, process specifications and several assumptions such as total working hours per day, machine utilization rate (UR), biomass conversion rates, BSF rearing parameters, and machine performance factors. In this development, the production type is defined as a continuous process that has a continuous flow of raw material through the sub-processes. Therefore, the amount of input material that a process is desired to handle, equals to the amount of output material from the preceding process. By using this method, the desired capacity of each sub-process was determined.

Table 2: Assumption of annual production performance

Assumption	***Unit***	***Unit***
Utilization rate	70	%
Working hours per day	24	h
Working hours per year	8760	h
Working minutes per year	525600	min
Biowaste capacity	4000	tn/a

Table 3: Desired processing capacity of the sub-processes

Process	***Operation***	***DCapacity1***	***Unit1***	***DCapacity2***	***Unit2***
Pre-processing	Waste reception	10.87	kg/min	1.09	m^3/h
	Waste crushing	10.87	kg/min	0.65	ton/h
	Waste mixing	10.87	kg/min	0.82	m^3/h
	Waste partitioning	10.87	kg/min	1.09	box/min
Rearing unit handling	Feed weighing	10.87	kg/min	1.09	p/min
	5-DOL partitioning	0.06	kg/min	1.09	p/min
	Palletizing/ Depalletizing	-	-	1.09	box/min
	Box washing	-	-	1.09	box/min
Warehouse rearing	Rearing unit storing	-	-	0.06	pallet/min
Post-processing	Larvae and frass seperation	2.07	kg/min	123.94	kg/h
	Larvae drying	0.97	kg/min	58.12	kg/h
	Larvae oil extraction	0.43	kg/min	25.83	kg/h
	Larvae packaging	0.30	kg/min	0.83	bag/day

$$DCap = \frac{TCap}{WorkTime \times UR} \tag{1}$$

where DCap is the desired capacity of the processing, TCap is target annual capacity, WorkTime is total annual working time and UR is the utilization rate.

Table 2 presents the assumption of annual production performance. The target annual processing capacity of the facility is about 4000 tonnes of biowaste. From this target annual capacity, the desired capacity of waste to be processed can be determined by using Equation 1. As all input and output materials of the production are known, the amount of material flow through sub-processes was calculated from the desired capacity of waste processing by using the law of conservation of mass and the given conversion rates of the BSF treatment.

When calculating the desired capacity of the sub-processes, the unit of a capacity value can be converted to other units based on the properties of handled material. For example, the capacity of the partitioning process was calculated from the capacity of the waste reception as an amount of mass per day, per hour or minute. However, the capacity was also converted to the number of boxes per hour or minute. This is useful for comparing the desired capacity with the actual capacity of machinery and equipment. Table 3 presents the calculated capacity of the processes with converted units.

4.3 Process machinery selection

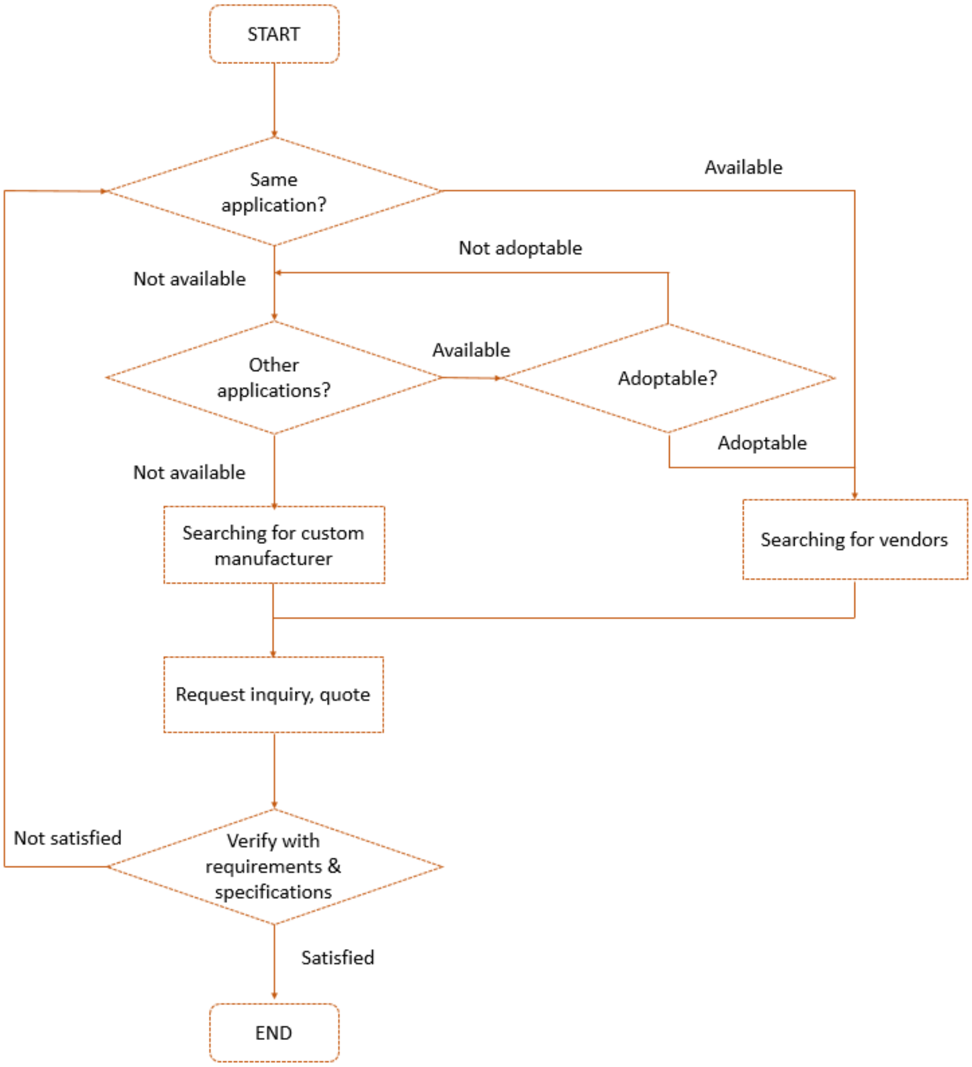


Figure 25: Machine selection strategy

The machinery searching and selection were implemented based on the required operations and calculated capacity of the sub-processes. Machines and equipment were categorized into two types: machines for fulfilling the desired operations of processes and material handling equipment for transporting materials among machines and processes. The strategy of finding suitable machinery for the development was described by the flowchart in Figure 25.

Table 4: Several common information included in an inquiry request

Aspect	***Information***
General information	Contacts, the field of industry, request machine type, etc.
Operation information	Type of operations, objectives, methods, etc.
Handled materials	Type of material such as food, feed, waste, chemical, etc. Properties of material such as bulk density, size, moisture, corrosive, toxic, explosive. etc.
Requirements	Desired capacity, contained volume Final product type, aim of products Final product properties such as size, density, texture, moisture, etc. Any special features

Table 5: List of main machine and equipment selected for the development

Category	***Machine and equipment***	***Function***
Process operation	Bunker, live bin	Receiving and transfering material
	Shredder	Size reduction for wet material
	Batch mixer, continuous mixer	Blending and mixing material
	Steel tank, silo with discharge auger	Storing and buffering material
	Load cell, weighing machine	Scaling and weighing
	Palletizer robot, palletizer mechanism	Palletizing boxes onto pallets
	Box washing machine	Cleaning dusty harvested boxes
	Box stacker and destacker	Buffering plastic boxes
	HVAC system	Climate controlling
	Sieving machine	Product separation
	Microwave belt dryer	BSF larvae drying
	Oil press machine	Extract oil from larvae
	Bulk bag filler station	Bulk bag packaging
Material handling	Screw conveyors, screw bottom, screw feeder	Wet and granular material transporting
	Belt conveyors, roller conveyors, chain conveyors	Container transporting
	Screw compactor conveyor	Dewatering and transporting wet material
	Front loader, forklift, automated forklift	Bulk material transporting

Firstly, machinery was investigated from the BSF production industry. Any available machine and equipment that was able to fulfill the desired operations were selected for the vendor searching phase. As the mass production of insects for feed and food is not currently a common enterprise, there are not many machines and equipment that specifically manufactured for the BSF industry. Therefore, it was inevitable to search for machinery from other industrial applications which could be able to adapt to fulfill the functionalities and operations of the production. These types of machinery then were selected for the vendor searching phase. Custom manufacturing was an option in case no ready-made machinery available for specific functions.

When a machine and equipment types were found, vendors or suppliers were searched. The local vendors were put in priority for agile supports and maintenance services. Brands and experience were also considered as criteria. Sending inquiries and quotes were the next phase for requesting technical information and the performance of the selected machinery. Table 4 presents several common information that should be provided to a vendor. The provided technical information from vendors was used to verify the machines and equipment with the requirements and specifications of the processes. Table 5 summarizes the selected machine and equipment for the desired operations and functionalities of the processes.

4.4 Automated processes designing

In this section, the designs of automated operations for sub-processes are presented from Section 4.4.1 to Section 4.4.4. The designing was implemented for each sub-process through six steps shown in Figure 26.

The first step was to determine automated operations to fulfill the desired operations and functionalities of each sub-process. After that, the second step was performed to select machinery listed in Table 5 which could provide defined automated operations in the previous step. The next step was to design the sub-processes by sketching the physical integration of machines and material handling equipment. After achieving a solution, the verification step was executed to verify the designed processes with the requirements and specifications. The fifth step was to analyze and select the most suitable design. Finally, the machines and equipment of the selected design were 3D-modeled to generate the floor layout and 3D visualization.

Figure 26: Automated process design steps

4.4.1 Pre-processing

The pre-processing process was designed to perform the pre-treatment operations of biowaste into a feed mixture for BSF larvae. Four main required operations were: receiving and feeding biowaste, size reduction, waste mixing, and automated material transportation. For receiving and feeding waste to the production, two options were considered: a live bin with screw bottoms and a concrete receive bunker with screw bottoms. For size reduction of biowaste, an industrial shredder was selected and for waste mixing, as it is suitable for processing large amounts of bulk wet materials. For waste mixing, a batch mixer and a continuous mixer were used to examine batch and continuous processing. Screw conveyors and screw bottoms were used to transport wet biowaste among machines. By integrating the machinery, three designs of the automated process were achieved which are presented in Figure 27, Figure 28 and Figure 29.

As can be seen from Figure 27, the first design consists of a front loader, a live bin, a shredder, a batch mixer, and two tanks. In this design, a front loader is required

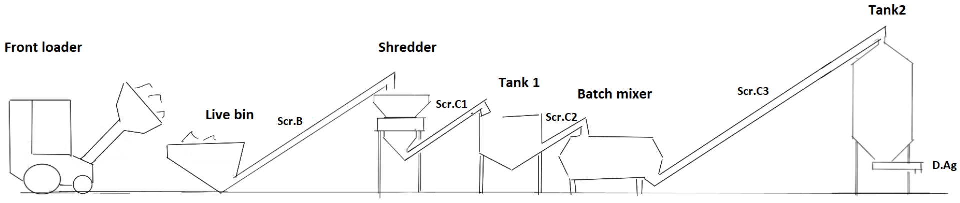


Figure 27: First design of pre-processing automation

to feed the raw material to the live bin. The live bin is attached with screw bottoms Scr.B that contain two or more screws to transport bulk waste. These screw bottoms continuously feed the biowaste to the shredder. Inside the shredder, the raw material is crushed into small pieces and then discharged by screw conveyor Scr.C1. Tank 1 receives and stores the shredded waste until the batch mixer is available. The mixer operates a batch mixing which does not maintain the continuous flow of material. The batch mixing consists of three stages: loading material, mixing and unloading ready mixture. In the loading stage, the mixer is idle, discharge conveyor Scr.C3 is off while infeed conveyor Scr.C2 loads the shredded waste from tank 1. When the limit of waste is reached, infeed conveyor Scr.C2 is turned off, the mixer starts to run while discharging conveyor Scr.C3 is still off. When the mixing completes, the mixer goes to idle, discharging conveyor Scr.C3 starts to unloading the ready mixture to tank 2, while infeed conveyor Scr.C1 is till off. After the unloading finishes, the mixer starts a new batch with the loading stage. The ready mixture is stored in tank 2 and is partitioned into boxes by discharge auger D.Ag of tank 2.

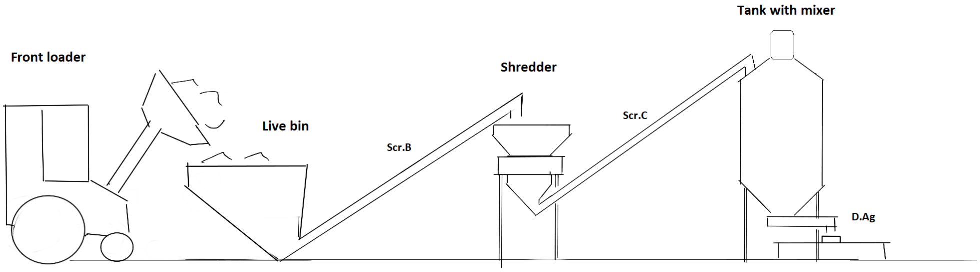


Figure 28: Second design of pre-processing automation

Figure 28 demonstrates the second design of the pre-processing process. This design was developed from the first one by replacing the batch mixing with continuous mixing. As described above, the batch mixing consists of three stages which require tank 1 and tank 2 to act as buffering components while the mixer is running. It also requires an amount of downtime for loading and unloading material. The batch mixer may provide a better quality of homogeneous mixture by mixing an amount of waste in a specific period. However, when storing the mixture in tank 2, it may cause dewatering for upper layers and the lower layers may absorb the water and become wetter. A continuous mixer may be able to produce a satisfying quality of waste mixture while does not need to have extra tanks for storage and buffering. A vertical continuous mixer can even perform both the mixing and buffering functions. It can also maintain the continuous flow of material from the shredder to its discharge auger. Besides, the mixer can continuously blend the new material with the old mixture, and keep a dynamic flow inside all the time. Therefore, it is worthy to consider continuous mixing as a promising solution for the mixing process.

The operation of this design can be described as simpler than the former design operation. Biowaste is fed into the live bin by a front loader. The live bin receives the waste and transports it to the shredder using screw bottoms Scr.B. After being crushed by the shredder, the material is then transferred directly to the mixer by screw conveyor Scr.C. The mixer loads the material until it gets a defined limit and starts mixing and then partitioning continuously via its discharge auger D.Ag.

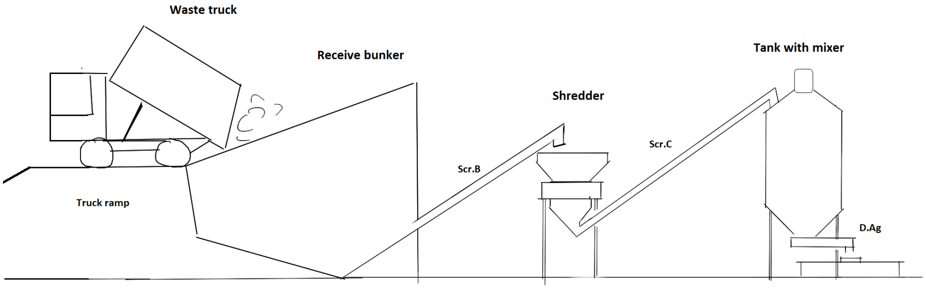


Figure 29: Third design of pre-processing automation

The third design of the pre-processing is presented in Figure 29. In this design, the live bin with screw bottoms is replaced by a concrete bunker with screw bottoms. This bunker can receive a large amount of biowaste directly from a truck. After that, it can automatically infeed the waste to the shredder during the day without using a front loader. Due to the cost of track ramp construction versus the cost of long screw bottoms, the bunker can be considered to be on the ground or underground.

4.4.2 Rearing unit handling

The rearing unit handling process was designed to achieve four automated operations: box partitioning, palletizing, depalletizing and box cleaning. The main components of the process, as illustrated in Figure 30, include:

- a load cell conveyor to weigh the mass of boxes,
- an automatic linear weigher to partition 5-DOL,
- an industrial palletizer robot to palletize and depalletize boxes,

- a box washing machine to clean harvested boxes,
- a box stacking and destacking machine to collect and dispense boxes,
- belt conveyors and roller conveyors to transport boxes, and
- two flipper mechanism structures to flip the boxes.

As calculated from Table 3, the palletizing throughput is 1.09 box/min. Base on similar robot palletizing systems, it was concluded that the robot could operate at a much higher speed of about 15 box/min. Hence, in this process, the palletizing station both loads new rearing units and unload harvest units. Figure 30 demonstrates the design of automated operations for the rearing unit handling process.

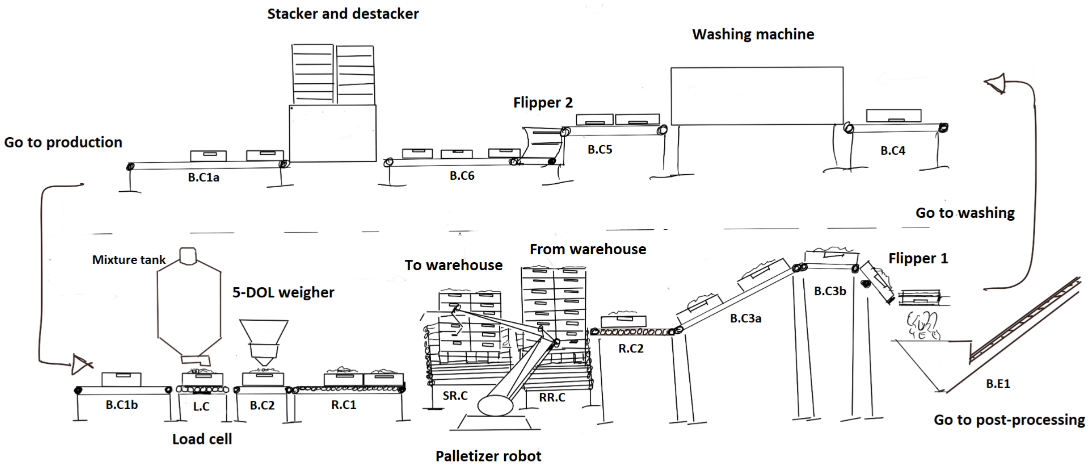


Figure 30: Design of the rearing unit handling process

The operation can be described as a production line of rearing boxes. In the beginning, empty boxes are dispensed from the box stacker and destacker to the load cell conveyor via belt conveyors B.C1a and B.C1b. The boxes stop on the load cell conveyor L.C and receive a partitioned mixture from the mixture tank of the waste pre-processing unit. The load cell weights the mass of boxes during the filling. When the boxes reach the desired amount of mixture, the load cell conveyor will move the boxes to the belt conveyor B.C2. Boxes stop under the linear weighing machine to receive 5-DOL. The linear weighing machine automatically drops a small amount 5-DOL into each box. Filled boxes then are moved to the palletizing station. The filled boxes are collected by roller conveyor R.C1 and remain there until being picked up by the palletizer robot. The robot picks up the filled boxes and places them on a pallet on the sending roller conveyor SR.C. Next, the robot picks boxes on the harvested pallets on the receiving roller conveyor RR.C and places them on roller conveyor R.C2. After that, the robot goes back to continue loading and unloading new boxes. The sending roller conveyor SR.C is where new ready pallets are sent to the rearing warehouse and the receiving roller conveyor RR.C is where harvested pallets are received from the rearing house to be unloaded. Harvested boxes after received by R.C2 are transported by belt conveyors B.C3a and B.C3b to a flipping mechanism to pour the larvae and frass into the hopper of belt elevator B.E1. Next, the empty boxes are transferred by belt conveyor B.C4 to a box washing machine to be cleaned. Another flipping structure is put in the output line B.C5 of the washing machine to overturn the cleaned boxes. Cleaned boxes are then transferred by belt conveyor B.C6 and are collected by the stacker and destacker and will be sent back to the production. In this system, the stacking and destacking machine act like a box dispenser but it can store several stacks of boxes for buffering.

4.4.3 Warehouse rearing

This section is to present the planning of warehouse rearing. Two main operations of the warehouse are to control environmental conditions and to store the rearing units. However, the controlling environment can be implemented by HAVC systems and is not included in the scope of the thesis. In this section, four steps were executed to plan the storing operation of the warehouse including: desired storage capacity calculation, transportation selection, storing method selection, and warehouse layout and warehouse operations planning.

The calculation of the desired storage capacity was performed using the data from the processing capacity calculation. As shown in Table 3, with a utilization rate of 70%, 0.06 pallet is prepared per minute which equals 86.4 pallets in 24 hours. However, the utilization rate is only applied to machines as it refers to the percentage of the actual running time of machines. Hence, only 70% time of a day the rearing pallets are actually handled which can be calculated as about 60 pallets produced per day. Using this number with the required rearing time of 20 days and desired redundant slots for buffering, a total storage capacity of the warehouse can be obtained which is about 1230 pallet slots. After getting an estimated desired storage capacity, a storage method was selected to obtain a suitable solution among several main methods: on-floor storage, static racking, and mobile racking.

For transportation, two vehicle types were considered, including man drive forklift and automated forklift. To decide a suitable solution, several factors were considered including transportation frequency and the required number of vehicles. The transportation frequency was calculated as 3.6 pallet/h for sending to warehouse and 3.6 pallet/h for harvesting from the warehouse. So in total, there are about 7.2 pallets required to be transported per hour which can be seen as a small number. Therefore, an automated forklift could be selected to eliminate much paid free time when using a forklift driver. However, this decision was required to be verified with the required transporting time per transportation cycle. The transporting time was calculated after completing the planning of storage layout and schedule.

In the storage system selection, four criteria were examined including storage capacity, space utilization, and investment cost. Three options were considered, including: on-floor storage, static racking, and mobile racking. On-floor storage means pallets are placed on the floor of the warehouse. This is the cheapest solution as it does not require any construction. However, for insect rearing, it is only suitable

Table 6: Warehouse planning calculation

Parameters	Quantity	Unit
Pallet width	0.6	m
Pallet length	0.8	m
Number of input/output pallets per day	60	$pallet/day$
Number of input/output rows per day	2	row/day
Number of pallets per row	30	$pallet/row$
Number of redundant row	1	row
Total stored day	20	$day/batch$
Total rows in warehouse	41	row
Total pallet slots	1230	$slot$
Width of forklift	0.99	m
Width of row	1.19	m
Overall length of forklift	2.413	m
Width of working aisle	3.5	m
Rearing area width	48.79	m
Rearing area length	21.5	m
Total area of rearing warehouse	1049	m^2

to use one layer storage to supporting the ventilation. Static racking is a system where pallets are put on several layers of static racks. Hence, this system is often used to store a large number of pallets where space is limited. However, the racking system requires construction investments, aisle lanes and high reach transportation. The last option is a mobile racking system that contains automatic movable racks to reduce aisle lanes, therefore, it requires high investment cost. Considering the capacity of 1248 pallets slots, which is not a large storage quantity, the on-floor storing method was selected as the most suitable solution. It does not require an investment for construction and space is not strictly limited. Also, unlike stacking on several levels, storing pallets in one layer on the floor is more beneficial to the rearing ventilation.

Once a storing method was selected, the warehouse layout was then designed to determine warehouse operations as well as the required space. As the rearing units are transferred daily and all are harvested in 20 days, rearing units should be organized such that the units are easily stored and retrieved based on their storing date. Putting the rearing units produced on the same day together on the same rows was determined as the simplest way to track the units. Table 6 presents the calculation to plan the layout of the rearing warehouse. As can be seen from the table, all produced pallets are moved in into two rows per day. In order to store one batch of 20-day-rearing and with a redundant row, the total rows for storing were calculated as 41 rows. Using the calculation data such as the size of pallets, size of transport vehicle, free aisle width and row width, a layout of the warehouse was designed.

Figure 31 demonstrates the layout as well as the operation of storing and retrieving

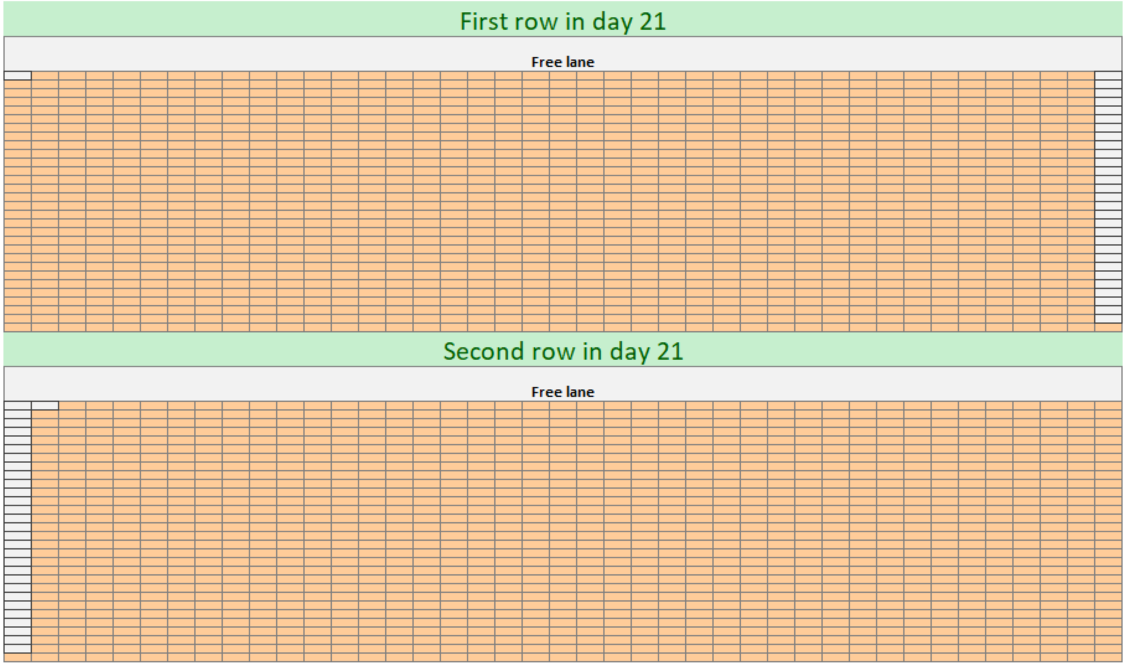


Figure 31: Demonstration of warehouse layout as well as an example of the storing and harvesting operations

pallets of the warehouse. Each cell represents a pallet slot in a row, each row contains 30 slots. In this organizing, each row has an identity to store its information such as occupied quantities, date of production and date to be harvested. In the first 20 days, 40 rows will be filled with produced pallets. Start on the day of 21^{st}, in each cycle of transporting, one new pallet is moved in and one 20 day-old pallet is moved out. As can be seen from the figure, in the first cycle of transporting on the day of 21^{st}, a pallet is moved into the row 41, and a pallet is harvested from row 1. When the row 41 is full, row 1 is also empty and is available to be filled with the remaining produced pallets on that day. The storing and harvesting operations are then repeated following this procedure. The warehouse layout and the operation of storing and retrieving were used to calculate the average transporting time per cycle of the transportation to estimate the required number of transport vehicles in the warehouse and to decide the selection of vehicle types.

4.4.4 Post-processing

This section presents the designing of the post-processing unit to obtain the automated operations of product refining processes. The desired operations include: frass and larvae separation, larvae drying, oil extraction and bulk bag packaging. The main components of the process, include:

- a vibration round screening machine (siever),
- a microwave belt dryer,

- an oil press machine,
- a semi-automated bulk bag filler with discharge roller conveyor,
- belt elevators,
- screw conveyors, and
- screw feeders.

A vibration round screening machine was selected to sieve the harvested substance. Using vibration generated by a motor, it can automatically and continuously sieve the infeed substance and discharge the materials from separated outlets. For the drying process, a microwave belt dryer was selected which was found as an exclusive machine for BSF larvae. With this dryer, there is no need to have an extra killing process such as boiling or freezing as the larvae are killed quickly by heat after entering the heating tunnel. The dryer also provides a continuous flow of material which is ideal to integrate into the continuous refining process. To extract liquid from larvae protein after drying, an oil press machine was chosen. It is widely used for oil extraction of various materials such as seeds, nuts, and insects. For packaging final larvae protein, a semi-automated bulk bag filler was decided as a relevant solution because the packaging frequency calculated in 4.2 was very low, about one bag per two days. Belt elevators, screw feeders, screw conveyors and pallet roller conveyors were used for transporting the materials with different forms, shapes and moisture levels. Although screw feeders or screw conveyors are used for a wide range of materials for inclined conveying, it is suitable to use belt elevators to prevent shredding of wet alive larvae. The screw conveyor was used to transport frass and the screw feeders were used to conveying high-temperature larvae after drying and oil extraction.

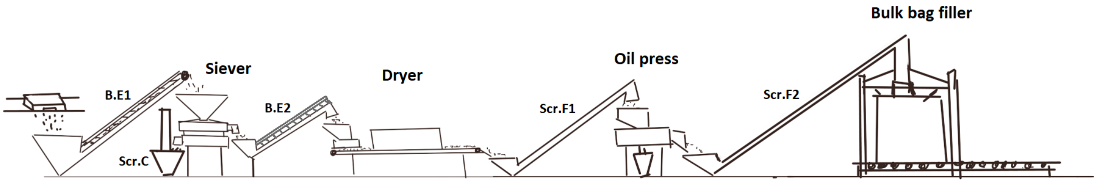


Figure 32: Sketching design of the automated post-processing process

Figure 32 demonstrates the design and operations of the automated post-processing process. After being poured from harvested boxes, the compound of larvae and frass is transported to the hopper of the sieving machine by belt elevator B.E1. The vibration siever continuously and automatically separates frass and larvae into two chambers. Frass falls through the mesh into the lower chamber and is discharged from the lower outlet. Screw conveyor Scr.C with a hopper is put under the outlet to collect and transfer the frass to storage or an outside bunker. Larvae remain on the top chamber and are then automatically discharged from the higher outlet. Belt elevator B.E2 then collects and feeds the separated larvae to the dryer. The dryer uses its belt conveyor to continuously move the larvae through the heating tunnel. After going out from the tunnel, the larvae are dried and are collected by screw feeder Scr.F1. Screw feeder Scr.F1 then transports the dried larvae to the oil press machine. This machine compresses the dried larvae to extract oil from protein. Extracted oil can be collected by a small container to pump into a tote tank. Concentrated protein is pushed out of the machine and transferred to the bulk bag filler inlet by screw conveyor Scr.F2. Bulk bag filler station has a cell load to weight the bag and a roller conveyor to discharge and buffer the packaged bags. As bag tightening and bag changing are complicated to be automated and the required packaging capacity is very low, a person is used to operate the packaging station.

4.5 Machinery integration

This section presents a method to integrate different machines and devices in the designed automated processes. To fully control the whole production process, it is vital to integrate the processes, machines, and devices into a system that can be controlled and monitored by operators. In order to establish a control system for the production facilities, two steps were implemented including determining suitable controllers for the processing units and examining the available communication interface to connect the devices, machines, processes, and operators.

4.5.1 Process hardware controller

To determine a control unit for a process, it is desired to define a suitable control technique for the process as continuous control or discrete control. Continuous control is intensive in handling analog signals using the proportional-integral-derivative (PID) control algorithm which is more suitable to use DCS controllers. In the other hand, discrete control focuses on treating ON/OFF discrete signals by logic and sequence control technique where PLC controllers are often used. Thus, the operations of each process were analyzed to obtain the control methods and relevant controllers.

Biowaste pre-processing unit maintains a feedstock flow through the shredder to the mixing tank. It is required to monitor the level of material in the tank within defined limits. The limits were defined as a low level to maintain the mixing process and a high level to avoid an overflow. A level sensor can be used to detect the limits and to send the feedback signal to control the input flow. This operation does not require to continuously regulate the speed of material flow regarding the change of level. It can be simply achieved by alternating two speeds of the infeed screw conveyors: a high speed when the level approaching the low limit and a low speed when the level reaching the high limit. Other operations in the pre-processing process were defined including machinery activation and safety stops. Thus, discrete control by using a PLC controller was considered as a suitable method to control the operation of the pre-processing unit.

Rearing unit handling process is required to control the operation of larvae feedstock partitioning and box handling systems. Feedstock partitioning handles the filling of the biowaste mixture into boxes with the same mass. A scaling controller is used to obtain high accuracy of filling by regulating the speed of the screw feeder according to the analog feedback signal from the loadcell. Larvae seeding into boxes is obtained by a vibration weighing machine that continuously weights and drops a small number of larvae. The scaling controller and the weighing machine act as a local controller and can be monitored by the operating states and parameter values by the process controller. Box handling systems consist of a conveyor system, an industrial robot, a box stacker and a destacker, and a box washing machine. The conveyor system, the machines, and the robot can be controlled via discrete states such as operation modes of machines, the single-speed motion of conveyors and positioning commands of robot gripper. In summary, since the rearing unit handling process mainly controls the operation states and discrete messages of machines and devices, discrete control and PLC controllers are selected.

Rearing warehouse has two main operations: climate control and pallet transportation. Climate control is implemented by a HAVC system which has its own separate controller. It can be monitored locally by HMIs and remotely via an operating software. Automated transportation is implemented by an automated forklift system. Automated forklifts have their own controllers and are monitored remotely by a management software which communicates with the production operation software.

The post-processing process has the main operation of refining products accomplished by machines and a conveyor system. The machines and the conveyor system can be discretely controlled using digital signals. The drying machine has several parameters that can be reconfigured locally via HMIs and remotely through the operating software. The packaging section is semi-automated so it is locally operated by a worker. Thus, a PLC is considered as a suitable controller.

4.5.2 Communication interface

In order to define the available communication interface of machines and equipment, they were classified based on in-built controller type: in-built PLC controllers, in-built microcontrollers and no in-built controller.

PLC controllers have a diversity of communication interface such as AS-i, Ethernet, RS-232, RS-485, 2-wire (I2C), I/O interface and Fieldbus. As mentioned in 3.2.8, Ethernet has been seen as the most common interface for the control network with many protocols such as Ethernet/IP, Ethernet TCP/IP, Modbus TCP/IP, and Profinet. I/O interface is used to directly connect field devices, such as sensors, switches, and relay, to the I/O module of the PLCs or to remote I/O terminals. In-built microcontrollers or so-called embedded controllers typically have several interfaces such as I/O, 1-wire, 2-wire (I2C), RS-232, RS-485, Ethernet, and Fieldbus. Equipment and devices without any controllers such as conveyors, sensors, motors, and servos can be connected to PLCs, drives or remote I/O terminals using the I/Os and power wire interface. The classification of machines and equipment based on controller types with available communication interface is shown in Table 7.

Table 7: Machinery classification based on controller types and communication interface

Controller type	Communication interface	Machine & Equipment
PLC	Analog and digital I/O, Ethernet, RS-232, RS-248, USB and so on	Shredder Mixing machine Box washing machine Sieving machine Microwave dryer Oil press Bulk bag filler Box stacker/destacker
Embedded controller	Analog and digital I/O, 1-wire, 2-wire (I2C), RS-232, RS-485, Ethernet, and Fieldbus	Scaling controller HVAC Linear weigher Industrial robot Automated forklift Motor drives
No controller	Power wire, analog and digital I/O, and Fieldbus	Belt conveyors Roller conveyors Screw conveyors Screw feeders Screw bottoms Loadcell Sensors

4.6 State machines for Automation control

This section will describe the designing of state machines to create IEC 61499 standard's control function blocks. The automated production process was divided into processing sections. The automation in each section will be controlled by a state machine. Section 4.6.1 will demonstrate a structure of the production automation system in which the processing sections are bounded and the required sensors are given. Next, the designing of the state machines for the automation control of the divided sections is presented in Section 4.6.2.

4.6.1 Production automation system

The final layout result of the production process, which will be discussed later in Section 5.2, was used to demonstrate the structure of the automation system. The process is divided into nine sections to distribute controllers within the system. The pre-processing area is named as section 1. The rearing unit handling area is divided into six sections: section 2A, 2B, 2C, 2D, 2E, and 2F. The AGV transportation is named as section 3_AGV. Lastly, section 4 comprises the post-processing area. The structure of the system is demonstrated in Figure 70 and is described below.

The pre-processing area is determined as section 1. It includes the bunker, the shredder, the mixer and screw conveyors. There are two ultrasonic sensors used in the section to provide level measurements. Sen1_1 is for the bunker and sen1_2 is for

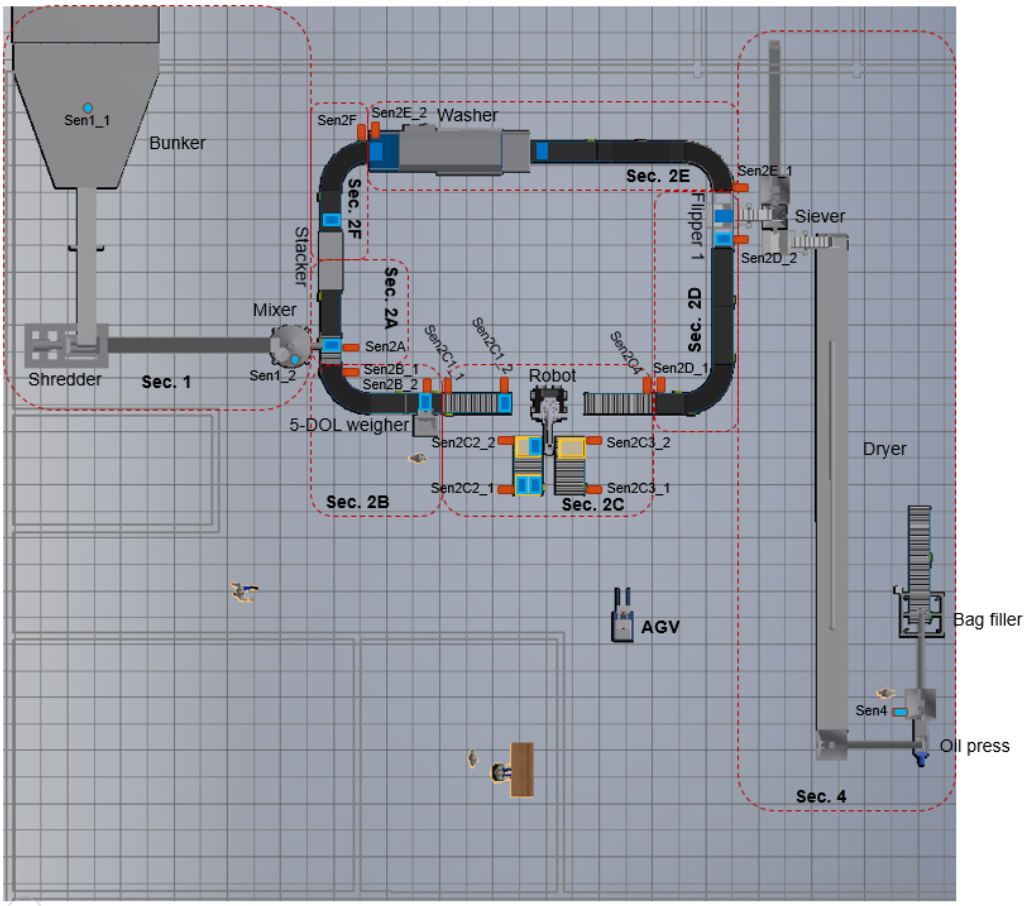


Figure 33: Sections of the production automation system

the mixer.

Section 2A consists of the destacking machine, the filling station, and its conveyor system. A photoelectric sensor, named Sen2A, is placed at the load cell conveyor to detect a box when it arrives at the filling position. The conveyors are controlled simultaneously to move the boxes through the section.

Section 2B involves the 5-DOL weigher and two separate segments of belt conveyors. One conveyor segment is to receive a number of filled boxes from section 2A and one segment to stop a box under the weigher. There are also two photoelectric sensors, Sen2B_1 and Sen2B_2, to detect the arrival of boxes on the conveyor system.

The palletizing and depalletizing area is defined as section 2C. It comprises a system of four roller conveyors and the palletizer robot. In this section, sensors are also placed in conveyor's ends to detect the arrival of boxes and pallets.

Section 2D consists of the harvesting flipping mechanism and the belt conveyor system. There are two segment conveyors which are controlled separately. A segment to transfer boxes to the flipper and another one to move the flipped boxes to section 2E. Two photoelectric sensors are used to detect the boxes: Sen2D_1 at the beginning of the first conveyor segment and Sen2D_2 at the flipping mechanism.

Section 2E is where the box washing area located. In this section, belt conveyors transfer dirty boxes to the washing machine. The washing machine uses its conveyor to continuously wash boxes and dispense cleaned ones at its end. Sensor 2E_1 is used to detect the arrival of dirty boxes and Sen 2E_2 is to recognize the cleaned ones before sending them to the next section: section 2F.

Section 2F involves the stacking machine and belt conveyors to collect and store cleaned boxes to send them back to the production. In this section, sensor Sen2F is put at the beginning of the receiving conveyor to provide feedback to the controller whenever a cleaned box arrives. The stacking machine is also able to send a signal when it collects a box.

AGV has the role of pallet transportation between the warehouse and the production site. It is identified as section 3. The AGV exchanges data and signals with section 2C and the warehouse to establish a transportation schedule.

The post-processing area is determined as section 4. It consists of processing machines, conveyors and feeders, and the semi-automated packaging station. The conveyors and feeders continuously transfer the material received from section 2D through the processing machines and dispense the final product at the packing station. As the last screw feeder stops each time the operator changes and tights a bag, Sen4, an ultrasonic sensor, is used to detect the larvae amount limits in the feeder hopper to ensure safety.

4.6.2 State machine design

This section will present the design of the state machine for the automation control of the production system. A state machine was created for each processing section in the system. In order to design the state machine, stable states, output signals and transition conditions from state to state in the behavior of the section were identified. Although the sections have different state machines, they have a similar design with major states, output signals, and transitions. A typical state machine designing is shown in Figure 34.

Five main stable states were identified in the state machines of a section, including initialization, idle, material receiving, operating, and material dispensing. The initialization state sets the value of output signals to the initial condition which is appropriate to the start of the operation. The idle state is when the section is not in use but ready to work. Material receiving defines the state that conveyors run to receive the processed material from the previous section and move it to the processing position. The operating state is when the section performs its desired operations. After the processing of the material is done, the system goes to the dispensing state. In this state, the section moves the finished material to the next section.

In the stable states, four main types of output signals were determined as machine monitoring commands, conveyor control commands, request signals to the previous section, and request signals to the next section. Output signals to machines and conveyors are to control and monitoring the material movement and processing operations. The requests to other sections are to establish a communication channel to ensure synchronization. When the section is available to receive the material, it will send a request to the previous section. When the section is ready to send the

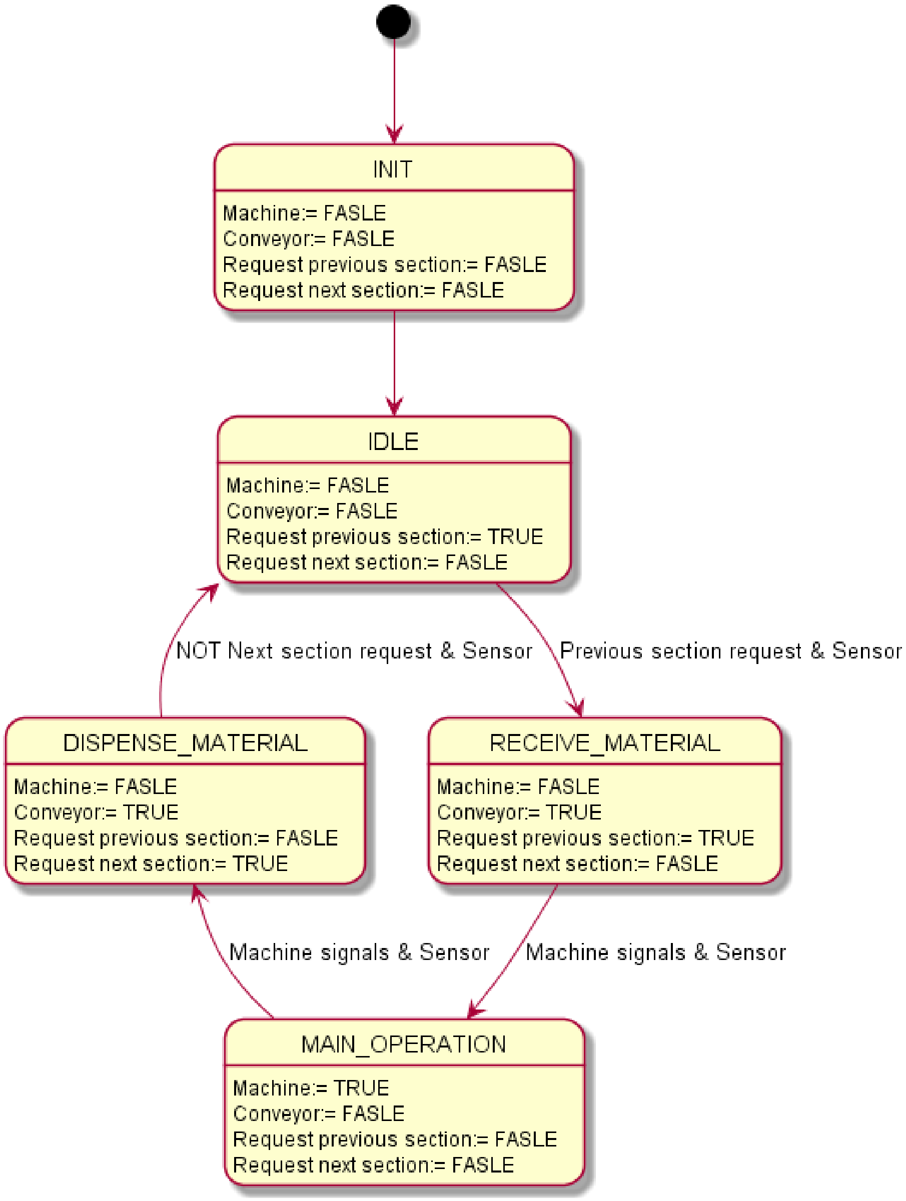


Figure 34: A typical designed state machine

material, it will request to the next section.

After the states and output signals were determined, transition conditions from state to state were defined. There are three types of transitions, including sections' requests, signals from machines, and sensors' detection and measurement. Requests from the previous section with additional sensor signals can enable the material receiving state from idle. Requests from the next section with sensor signals are used for the dispensing of finished material. Another type of transition is machine signals. They provide status and parameters of machine operations such as the status of 5-DOL dropped from the weigher. Sensor signals including level measurement and position detection are also used as the transition from state to state. For example, if the received material arrives at the processing position, the sensor detection can exit the receiving state and go to the operating state.

The details of the individual state machine will be shown in Appendix 7.1. These state machine designs can be used to develop software controllers for production automation. In this thesis, based on the state machines, IEC 61499 standard control function blocks are created. The results of the function blocks will be presented in Section 5.4 in the next chapter.

5 Results and discussion

In this chapter, the results obtained from the development are described and discussed. The final machinery list and capacity analysis are presented in Section 5.1 to provide the main components of the automated production process as well as to analyze the processing capacity. Section 5.2 shows the designed floor layout of the production process and its 3D visualization. The proposed control system is presented in Section 5.3 to explain the integration of machines and equipment into an automation control system. Finally, IEC 61499 standard function blocks created from the state machines are presented in Section 5.4.

5.1 Machinery selection and capacity analysis

In this section, the final machinery lists and the capacity analysis of the main machines are presented. As described in 4.3 and 4.4, the types of machine and equipment, which were able to automate the various operations within the production process, was first identified for the process designing step. The final list of machinery was then obtained from the most optimal designed solution. After that, the capacity of the main selected machines was compared with the desired capacity to examine the performance of the machine as well as to define the potential bottlenecks of the production.

Table 8: Types of selected machinery

Process	***Code***	***Operation***	***Machinery***
Pre-processing	1.1	Waste reception	Live screw bottom bunker
	1.2	Waste crushing	Shredder
	1.3	Waste mixing Waste partitioning	Vertical tank with mixer
	1.4	Material handling equipment	Screw conveyor
Rearing unit handling	2.1	Feed weighing	Load cell
	2.2	5-DOL partitioning	Linear weigher
	2.3	Empty box input	Box stacker/destacker
	2.4	Palletizing/ Depalletizing	Industrial robot
	2.5	Harvested box cleaning	Box washing machine
	2.6	Material handling equipment	Belt conveyor
	2.7		Roller conveyor
	2.8		Pallet roller conveyor
Rearing warehouse	3.1	Controlled climate	HVAC system
	3.2	Rearing unit transportation	Automated forklift
Post-processing	4.1	Larvae and frass seperation	Sieving machine
	4.2	Larvae drying	Microwave belt dryer
	4.3	Larvae oil extraction	Oil pressing machine
	4.4	Larvae packaging	Bulk bag filler
	4.5	Material handling equipment	Screw feeder

Table 8 present the selected types of machinery to automate each operation within the production process. As can be seen from the table, the selected machines and material handling equipment are categorized according to their main processes (1-4) and their desired operations (1.1-4.5). Several designs were considered for the pre-processing stage, and Table 8 shows the final selections. The most complex choices were related to waste reception and waste mixing and partitioning. For the waste reception operation, a bunker with live screw bottoms was chosen because it can receive waste directly from a truck, and can continuously and automatically feed the biowaste to the production process. This solution obviates the need for a driver and a front loader, which eliminates the dependence on human availability, and may be cost-effective in the long term. With regard to waste mixing and partitioning, a vertical tank with a mixer was selected in order to combine the waste mixing process with the partitioning function. The combination of mixer and tank simplifies the operations, makes the maintenance easier, as well as provides a buffer for material while performing continuous partitioning. In addition, the vertical design takes advantage of gravity to support the mixing process and the discharging of material better than a horizontal one.

After the machinery was defined, the capacity calculation of each machine was executed to analyze the performance of the machine and to define the potential bottlenecks of the production. Two types of capacity were used in the analysis including the desired capacity of the processes and the maximum capacity which a machine can handle. In Table 9, the desired capacity and the maximum capacity of machines are compared using analysis ratio numbers AnaRatio.

Table 9: Capacity calculation of the main machines

Code	***Machinery***	***D.Capacity1***	***Unit1***	***D.Capacity2***	***Unit2***	***M.Capacity***	***Unit***	***AnaRatio***	***Unit***
1.1	Live screw bottom bunker	10.87	kg/min	18.26	m^3/d	30	m^3	1.64	d
1.2	Shredder	10.87	kg/min	652.32	kg/h	1500	kg/hr	0.43	
1.3	Vertical tank with mixer	10.87	kg/min	0.82	m^3/h	3.3	m^3	4.05	h
2.1	Load cell	10.87	kg/min	1.09	p/min	10	p/min	0.11	
2.2	Linear weigher	0.06	kg/min	1.09	p/min	20	p/min	0.05	
2.4	Industrial robot	-	-	2.18	box/min	15	box/min	0.14	
2.5	Box washing machine	-	-	65.23	box/h	150	box/h	0.43	
3.2	Automated forklift	-	-	0.06	pallet/min	2.44	pallet/min	0.02	
4.1	Sieving machine	2.07	kg/min	123.94	kg/h	500	kg/h	0.25	
4.2	Microwave belt dryer	0.97	kg/min	58.12	kg/h	100	kg/h	0.58	
4.3	Oil pressing machine	0.43	kg/min	25.83	kg/h	80	kg/h	0.32	

Unlike the other machines, the receiving bunker and the mixing tank have AnaRatio numbers with time units of day and hour to indicate the buffering capability. The buffering capability of the two components is important to examine how they can eliminate external disturbance. As can be seen from the table, the maximum contained volume of the bunker is 30 m^3 and the total amount of waste processed in one day is 18.26 m^3. Dividing the bunker volume by the amount of one day processed waste, the AnaRatio was found as 1.64 d which means the bunker can feed the waste in about one and a half day if it is fully loaded at the beginning. Similarly, the AnaRatio of the mixing tank was found as 4.05 h which indicates that the tank has a buffering capability to feed the waste to the production in 4.05 h. The buffering time of these two is enough for handling any interruption of the infeed material such as fixing faults.

The capacity of other machines is analyzed by dividing the desired capacity by the maximum capacity of machines to get their AnaRatio values. If these values equal to 1 or very close to 1, it means the machines satisfy the desired capacity. If an AnaRatio value is greater than 1, it means the desired capacity exceeds the maximum capacity of the machine, and it may require more than one machine or a machine with higher capacity. However, the table shows that the values are much smaller than 1, it means the selected machine running at a very lower capacity that they can handle. Clearly, the facility is wasting resources, especially with machines that consume a constant amount of energy during production like a shredder. There are two solutions for this issue: selecting machines with lower capacity or increasing the whole processing capacity of the production. However, if there is no available machine with lower capacity in the market and there is enough source for biowaste, it is sensible to increase the processing capacity of the production. When increasing the capacity, it is important to detect the potential bottleneck of the system. The potential bottleneck has the highest AnaRatio value. It can be observed that the dryer is determined as the bottleneck with the AnaRatio of 0.58. Dividing 1 by 0.58 gives the result of 1.72 which means the processing capacity of the whole production can be scaled up to 1.72 times in order to obtain the maximum capacity of the dryer. If the processing capacity is increased greater than 1.72 times, it requires to use a dryer with a higher capacity or to use more than one dryer.

5.2 Factory layout design and 3D visualization

This section presents the design factory layout and 3D visualization for the production process. The factory layout and 3D visualization were generated to plan the needed space and location of process units and machinery as well as to provide a visualized operation of the production.

To create a factory layout and a 3D visualization at one procedure, AutoDesk software package including AutoCAD and Inventor integrated with Factory Design Utilities was used. The software provides one-to-one synchronization between 2D drawing and 3D modeling. Four steps were implemented to obtain the layout and 3D visualization including: collecting machinery dimensions, 3D modeling of machinery in Inventor, planning the 2D layout and synchronizing between 2D drawing and 3D visualization. The machinery dimensions were summarized from the technical information received from the vendors. The machine and equipment models were then designed based on the dimension and shape of the main components. In Inventor software, the machinery models were published to become factory assets which had both 2D drawing and 3D models. There were also ready-made models of several machines and equipment in the software library which could be modified according to actual dimensions such as belt conveyors, roller conveyors, industrial robots and automated forklifts. After getting all drawing of components, the 2D floor layout planning was executed according to the designed solutions described in 4.4. Material flows, connecting distances and location requirements were considered when planning the layout. Finally, 3D visualization was achieved by synchronizing AutoCAD drawing into Inventor modeling. The 3D visualization provided all dimensions of installation to define and verify the requirements of connection and integration among machines, equipment, and operators.

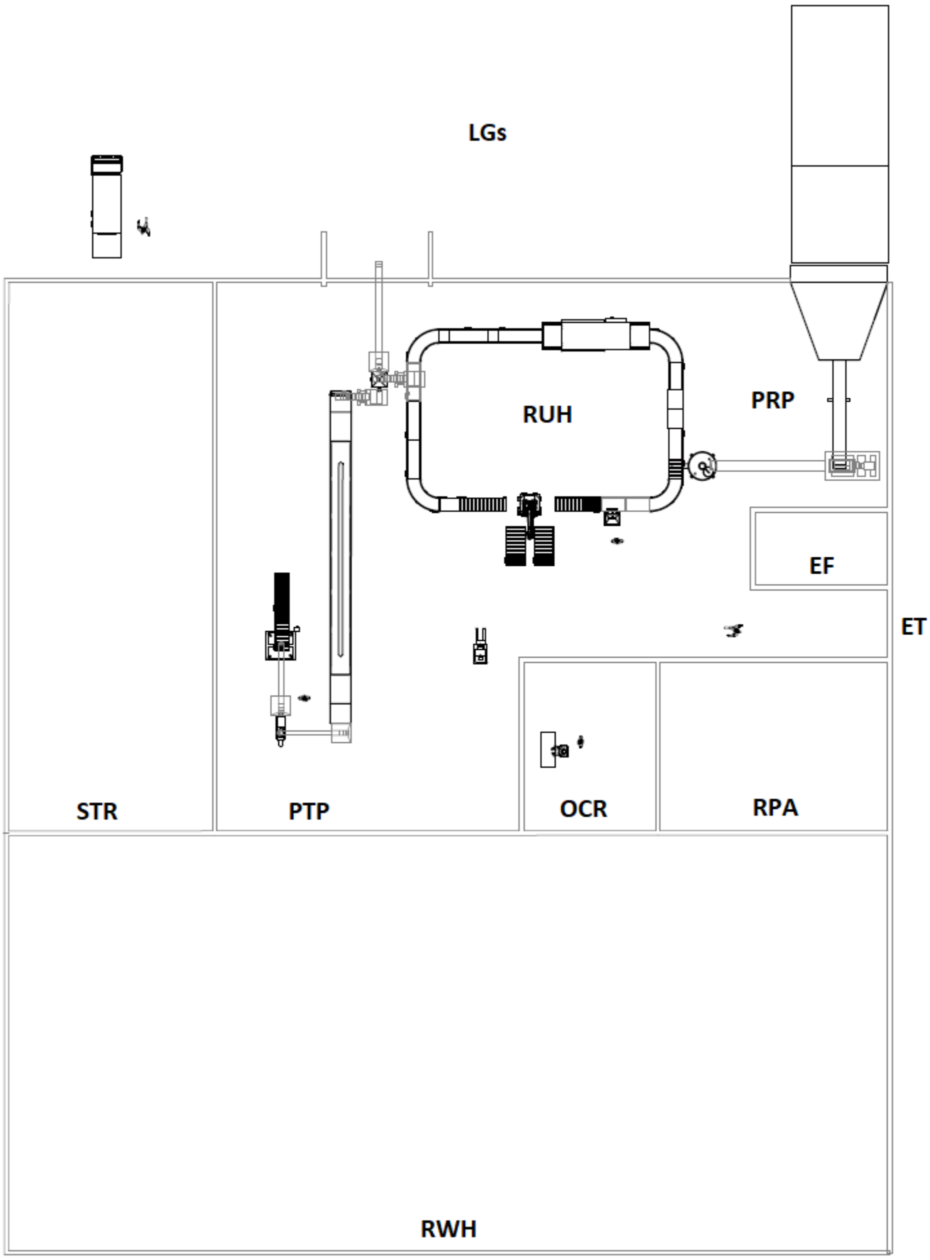


Figure 35: Floor layout of the automated facility; areas: pre-processing (PRP), rearing unit handling (RUH), rearing warehouse (RWH), post-processing (PTP), product storage (STR), operating control room (OCR), employee facility room (EF), 5-DOL reproduction area (RPA), logistic gates (LGs), entrance (ET).

Figure 35 presents the planned factory layout which shows the location of machinery and processing units. As can be seen from the figure, the waste truck port, the frass bunker, and product shipping ports are located in one site (LGs). This is sensible due to the common layout of renting factories which usually supports the outbound logistics operations. For inbound material flows, to ensure the hygiene of production, clean sites such as post-processing area and product storages are located away from dirty sites such as pre-processing area and employee facilities including toilets, showers, and lockers. To improve the dissociation, wall structure can be used between these areas. In order to generate efficient material flows, the processing areas are also considered to achieve a short moving distance of materials. 5-DOL reproduction area is placed close to the rearing unit handling area and the 5-DOL flow can easily reach the 5-DOL weighing machine. Also, it is located next by the rearing warehouse to share the control climate system such as heating exchanger and ventilation pipes. Efficient product transportation is obtained by organizing the product storage next to the packaging station. The operating control room is at the center of the factory in order to provide accessible reach to every area of the factory.

Table 10 presents the estimated required space for the production facilities which is obtained from the layout planning. As can be seen from the table, the largest area is the rearing warehouse with a required space of 1049.2 m^2. This number is acquired from the design of the rearing warehouse to store up to 1230 pallet slots on one level. For future upscaling, the warehouse can be upgraded with a racking system with more than one level. Pre-processing, rearing unit handling and post-processing area are defined after completing the floor layout of machines and equipment in those processes. The space of 5-DOL production, product storage, operating control room and employee facilities is estimated according to given data from expertise people who have experience in BSF production. This estimation can be verified with further planning work. The free lane area is calculated by subtracting the total area with allocated ones. The free lane space equals 235.3 m^2 as about 9.6% of the total area meaning that space is effectively utilized. It is worthy to note that the width of the free lane is planned wide enough for smooth and convenient traffic within the production facility.

Table 10: Estimated needed space

Site	Dimension	Area
Pre-processing	10.5 m x 11.7 m	122.9 m^2
Rearing unit handling	14.8 m x 14.8 m	219 m^2
Rearing warehouse	21.5 m x 48.8 m	1049.2 m^2
Post-processing	9.2 m x 24.6 m	226.3 m^2
5-DOL production	11.8 m x 8.9 m	105 m^2
Product storage	14 m x 28.2 m	394.8 m^2
Operating control room	6.7 m x 8.9 m	59.6 m^2
Employee facilities	6.8 m x 4.1 m	27.9 m^2
Free lane	-	235.3 m^2
Total	50 m x 48.8 m	2440 m^2

Figure 36 illustrates the 3D visualization of the automated production facility. The visualization provides a full dimension view of machinery installation and integration which supports to determine any issue of installation in height or any difficulty of

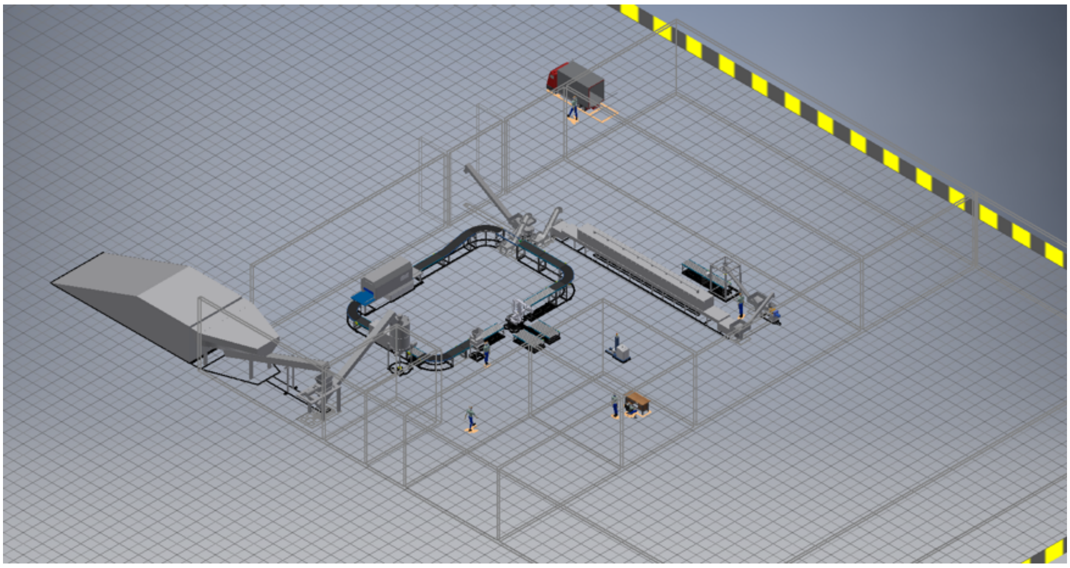


Figure 36: 3D visualization of the automated production facilities.

human operation. Figure 37 shows a zoom-in view of the pre-processing area. As can be seen from the figure, the screw conveyor between the shredder and mixing tank has inclined installation such that the underneaths of the conveyor provide a walking lane for operators to supervise the working of machines. It also points out that the shredder and the mixing tank require climbing platform for operator checking and maintaining.

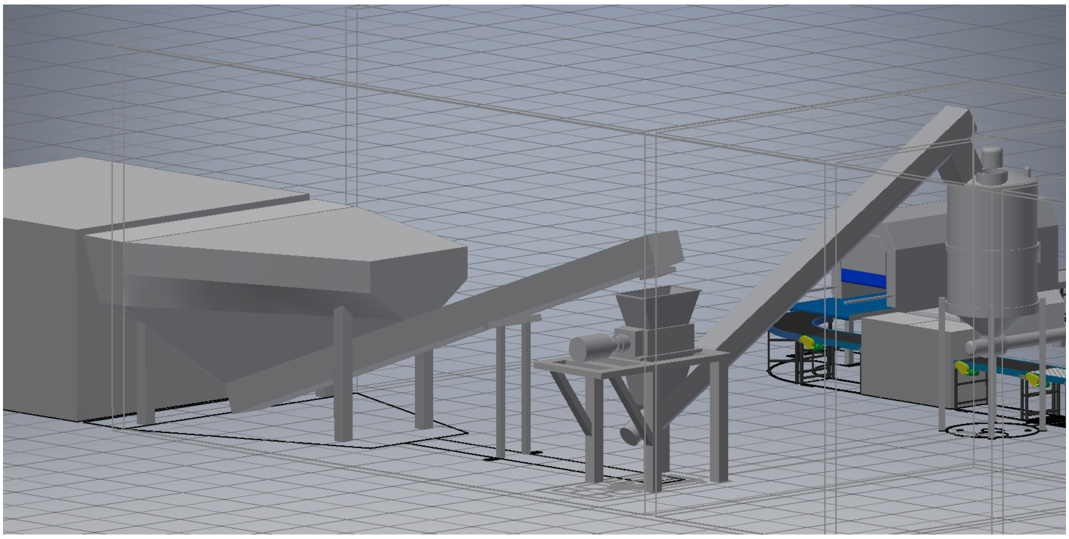


Figure 37: 3D visualization of the pre-processing process.

Figure 38 demonstrations the 3D view of the rearing unit handling process. On the scene, the linear weighing machine for partitioning 5-DOL is placed too high from the floor which is difficult for a worker to infeed 5-DOL into the machine hopper. It is clear that a climbing structure or a belt elevator is necessary to aid the feeding material of workers. A climbing structure like a stepping block can be used if the feeding frequency is low. However, if the production capacity increases, a belt elevator with hopper will ensure the safety of workers.

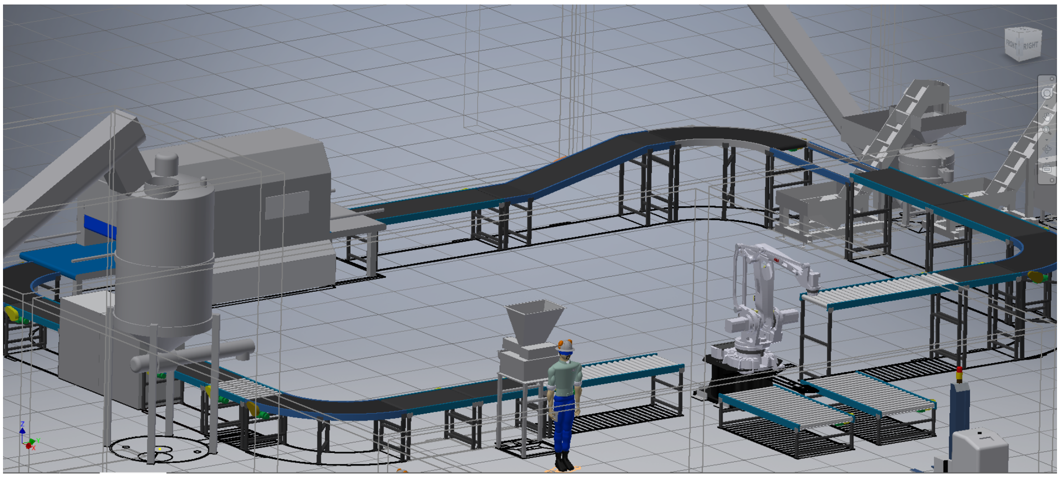


Figure 38: 3D visualization of rearing unit handling process.

Figure 39 shows the scene of the post-processing process. It can be seen that there are several issues with the connection of conveyors, feeders, and machines. The discharge port of the sieving machine for frass separation is too low and closed to the floor which does not fit the infeed hopper of the screw conveyor. Two possible solutions are increasing the installation height of the sieving machine or using a smaller screw conveyor with a smaller hopper. Similar issues occur with the discharging of dryer and oil press machines which can be overcome by better installations.

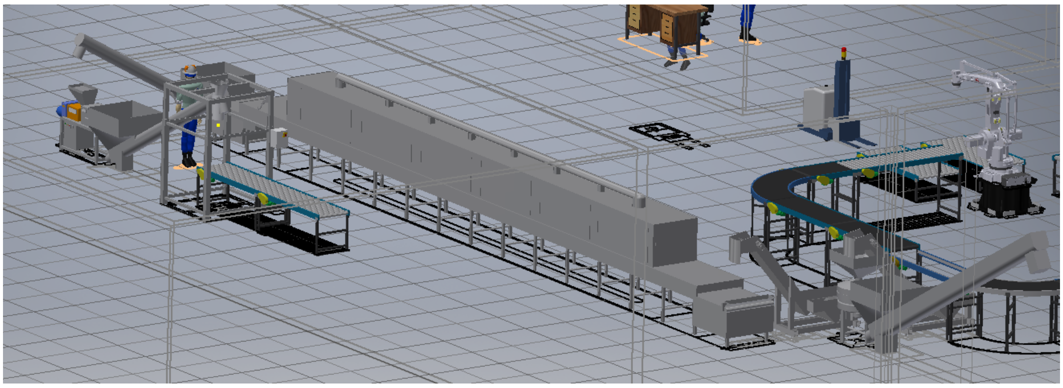


Figure 39: 3D visualization of post-processing process

5.3 Integration control system

In this section, an integration control system is proposed. The controllers and available communication interface of machinery determined in Section 4.5 were then used to establish networks to link the machinery, equipment, and operator monitoring together into a system. The control system consists of two networks: a field device network to connect field machinery to controllers; and a control network to connect controller units. Figure 40 demonstrates the structure of the control system.

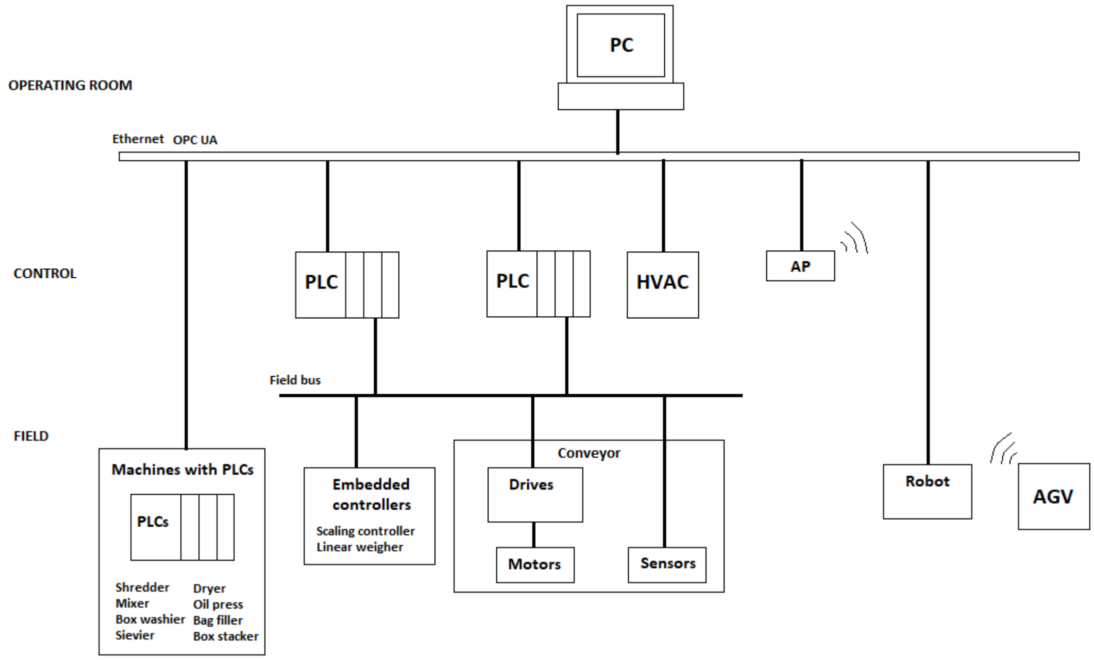


Figure 40: Integrated control system of the production automation

As determined in Section 4.5, the automated processes of the production can be controlled by PLCs. In order to support the possible scaling up and the maintenance in the future, PLCs are distributed to the processes or to the sections within the production system. As OPC UA is the standard communication for different controllers from various vendors, it is used with the Ethernet network to establish the control network to connect the PLC controllers and operator's PC together to exchange control data and information.

Field machines and equipment with inbuilt controllers that have an Ethernet interface, can connect directly to the Ethernet control network to exchange data with PLC controllers. These machines include inbuilt PLCs machines, the robot, HVAC, and AGV. As the AGV has wireless communication, a wireless access point (AP) is used to establish the connection from the fleet AGV to the Ethernet network. Other machines and equipment including scaling controller, 5-DOL weigher, and conveyors which do not have an Ethernet interface, are connected to PLCs via a Fieldbus network. However, the protocols for the Fieldbus are not determined in this thesis and still be an open question in future work.

5.4 IEC 61499 standard function blocks

In this section, state machines generated in 4.6 is used to create IEC 61499 standard's function blocks (FBs) using nxtSTUDIO for future software development. Each state machine is transformed into a FB to control the respective section. The result consists of eight FBs, including: SEC1Control, SEC2AControl, SEC2BControl, SEC2CControl, SEC2DControl, SEC2EControl, SEC2FControl, and SEC4Control. The state machine of section 3 can be used to program the schedule of the forklift AGV in the fleet management software and was not used to create IEC 61499 standard FBs.

Each FB contains an INIT input event and an INITO output event to initialize the value of output data, a REQ input event and CNF output event to update the value of output data according to the associated inputs. There are two types of input data: sensor and machine indicator signals, and request commands from other sections. Two types of data output are control signals to equipment and request commands to other sections. To create the control FBs for the production automation, basic type FBs and a composite FB were used. Basic type FBs were driven by The Executed Control Charts (ECCs) which were derived from the state machine discussed in 4.6. The ECCs are attached in Appendix 1. The composite FB was created by composing basic FBs to integrate multiple control functions. The following sections will describe briefly the designed control FBs of section 1, section 2A to F and section 4.

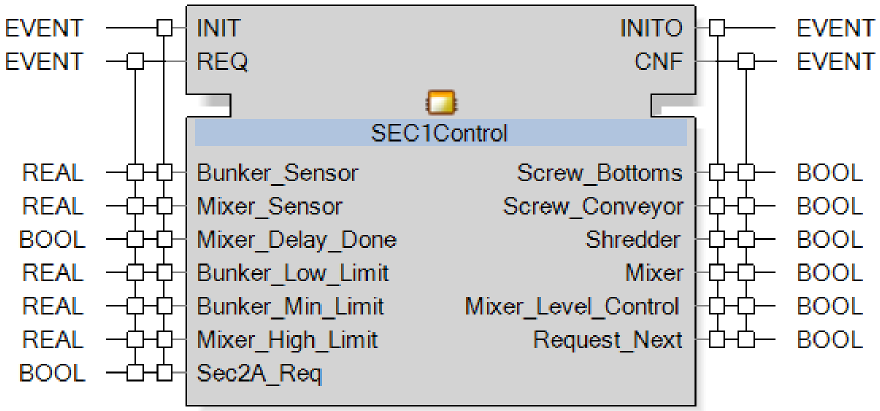


Figure 41: Control function block for section 1

Figure 41 illustrates the control FB SEC1Control of section 1. SEC1Control is the FB to control the pre-processing unit. It takes the level measurements and compares them to the level limits of the bunker and the mixer. According to the value of the level measurement and the condition request from the next section 2A, the block activates the control signals to the screw bottoms, screw conveyors, shredder, mixer and to the mixer level controller. It also sends signals to the next section 2A whenever section 1 is in processing mode and the waste mixture is ready to be partitioned.

Figure 42 shows the control FB SEC2AControl of section 2A, which control the box destacking and the waste mixture partitioning. SEC2AControl receives information from the box destacker, the position detective sensor at the filling position, and the scale controller as well as communicating to the next section 2B and the previous section 1. SEC2AControl also provides command signals to monitor the conveyor, the box destacking machine and the scale controller.

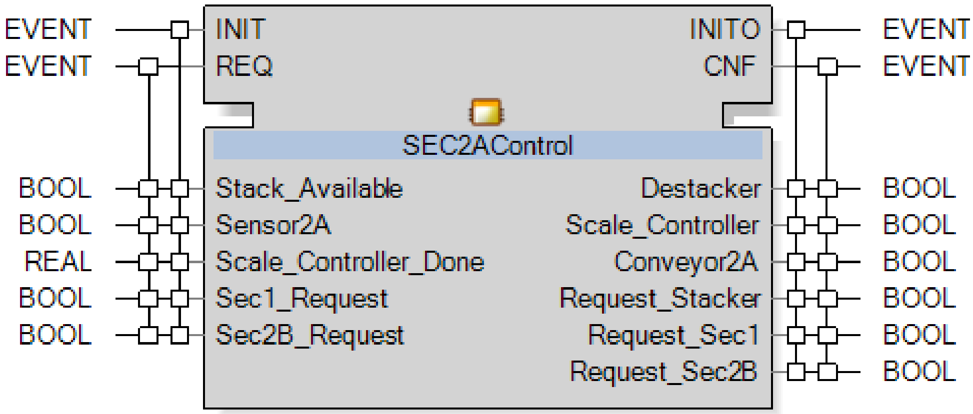


Figure 42: Control function block for section 2A

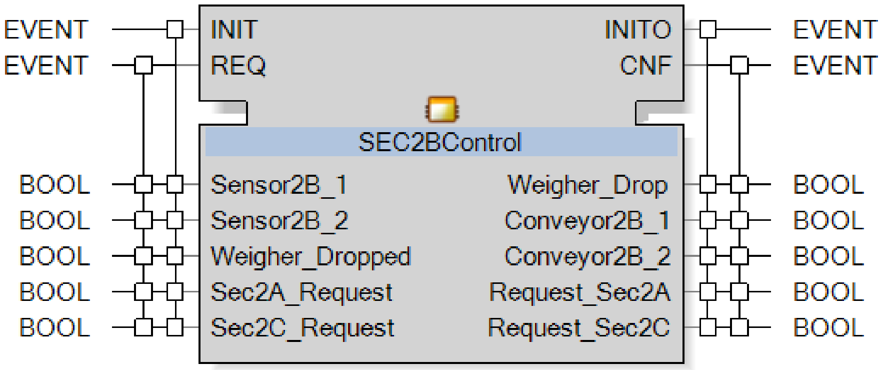


Figure 43: Control function block for section 2B

SEC2BControl block shown in Figure 43 is to control the 5-DOL partitioning operations. It receives input signals from conveyor sensors, the 5-DOL weighing machine, and requests from sections 2A and 2C. Based on the inputs, the control commands are generated to monitor the conveyors and the weighing machine as well as communicate back to section 2A and section 2C.

Figure 44 and Figure 45 present the composite FB SEC2CControl and its components. SEC2CControl consists of five customized basic type blocks to control four conveyors and to monitor the palletizer robot. The composite block collects data from the conveyors' sensors, the robot controller and requests from the forklift AGV system as well as from section 2B and 2D. The data and requests are then sent to the concurrent control FBs to generate their output signals. SEC2CControl will update

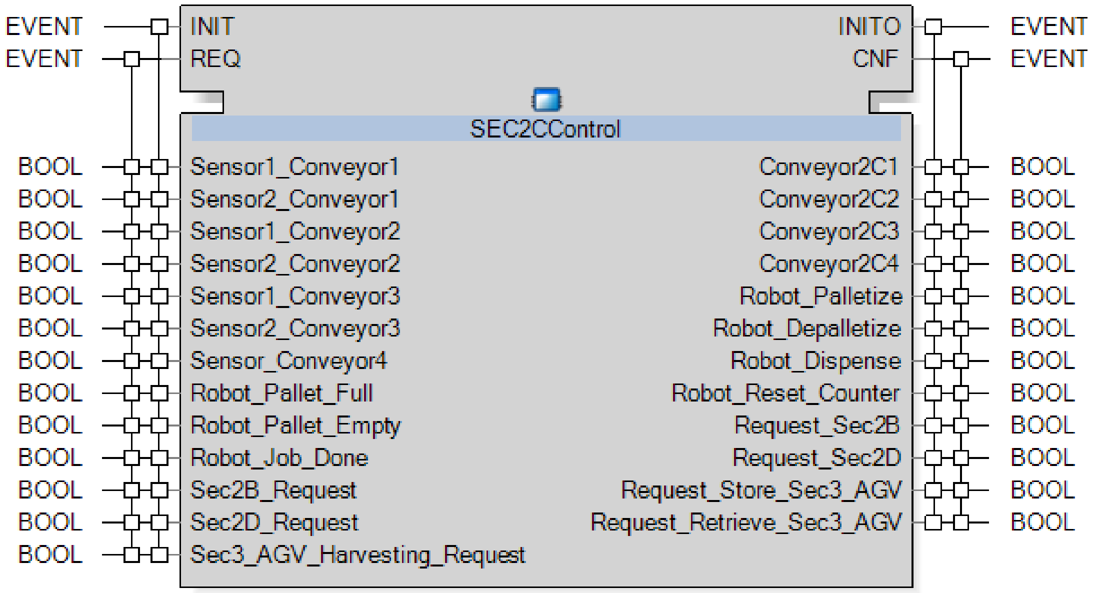


Figure 44: Control function block for section 2C

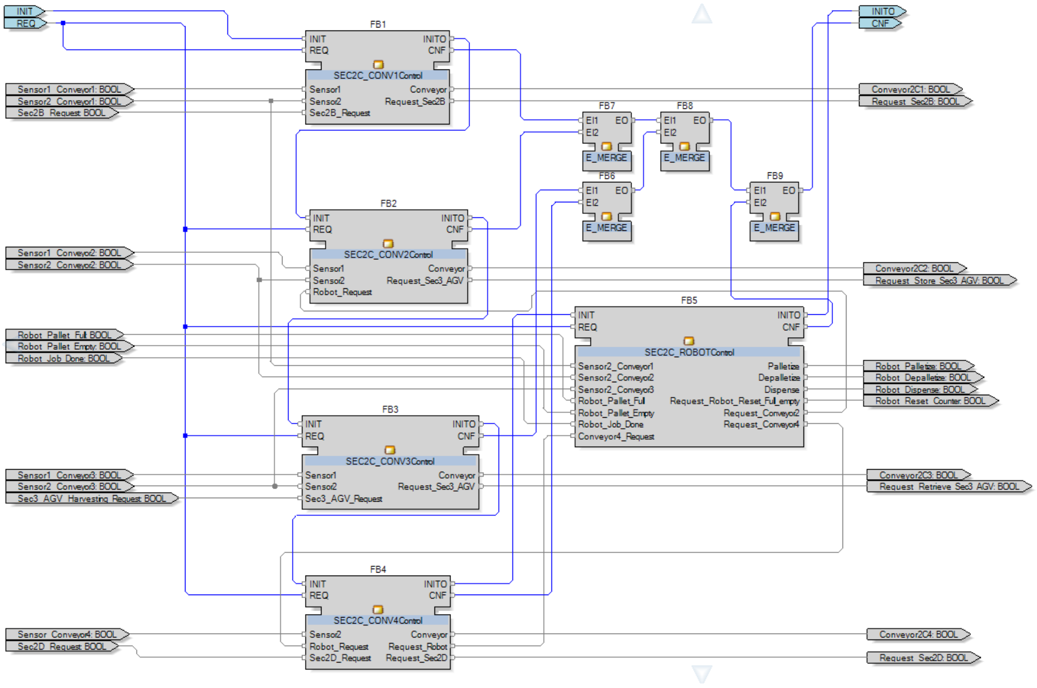


Figure 45: Composite function block SEC2CControl

the output data by merging the output events of the component blocks. It also sends request commands to the next and previous sections to ensure the synchronization among them.

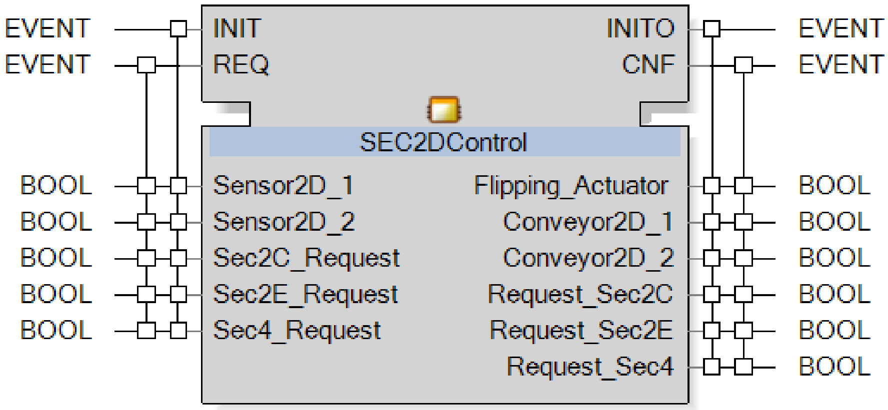


Figure 46: Control function block for section 2D

Section 2D, which handles the harvesting of the rearing boxes, is controlled by FB SEC2DControl shown in Figure 46. The block controls the flipping actuator and conveyors based on the detection of conveyor sensors and the communication with sections 2C, 2E and 4. It is a basic type FB and is directly executed by ECC derived from the respective state machine.

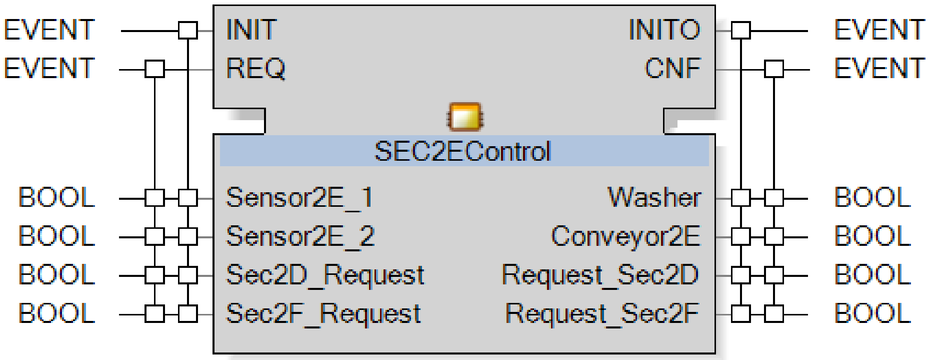


Figure 47: Control function block for section 2E

Figure 47 shows the designed FB to control section 2E. This block controls the conveyor system and monitors the operation of the washing machine. The washing machine has its own controller and is activated by command signal Washer. When Washer is activated, the machine runs its conveyor to continuously transfer dirty boxes through washing chambers. When Washer command is off, the machine stops transferring the boxes and washing chambers go to idle. SEC2EControl also carries out the communication to the next section 2F and the last section 2D.

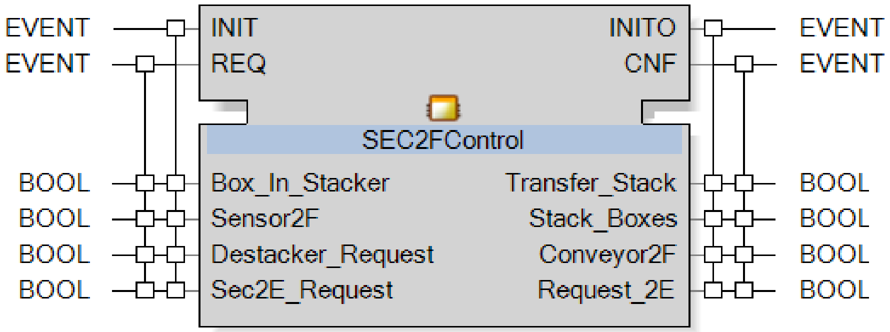


Figure 48: Control function block for section 2F

Figure 48 describes the FB to control section 2F where boxes are collected from the washing machine, buffered by the stacking machine and sent to destacking machine when they are needed. This FB connects its inputs to conveyor sensor 2F, to the stacking and destacking machine (Box_In_Stacker and Destacker_Request), and to section 2E. Output data consists of control commands for the conveyor and the stacking and destacking machine (Transfer_Stack and Stack_Boxes) as well as request command Request_2E to section 2E.

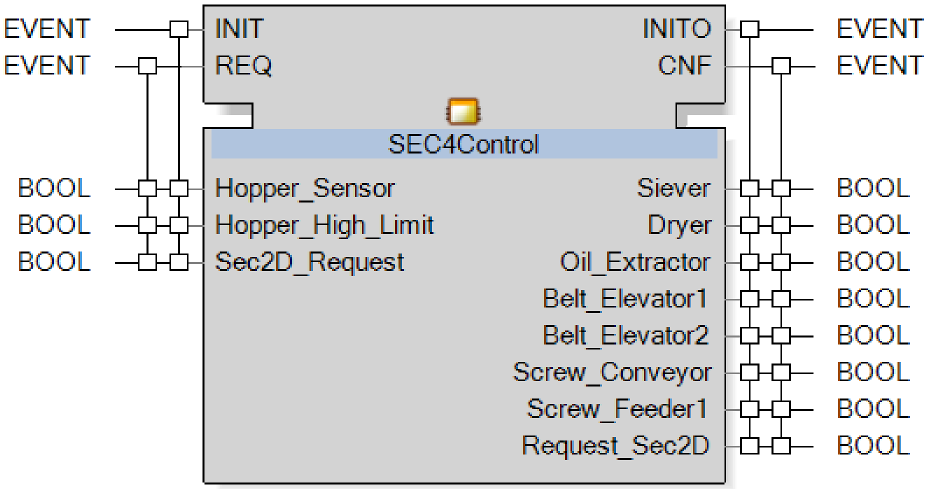


Figure 49: Control function block for section 4

SEC4Control shown in Figure 49 is for section 4 which controls the post-processing unit. The FB receives the hopper level measurements of the final protein product, a setpoint high limit level for the hopper and requests from section 2D. Output data is used to control the conveyor system and to monitor the product refining machines as well as to send requests to section 2D.

6 Summary

This thesis has proposed a development in the automation of Black Soldier Fly production, automating most of the manual work, and making the industrialization of production feasible. The solution developed consists of three components: a list of machinery with capacity analysis, a floor layout design and 3D visualization of the processes, and a proposed automation control system for the integration of machinery.

The list of machines and equipment demonstrates the availability of current technologies for the automation of BSF production. The selection of machinery was executed after the requirements, specifications, and desired processing capacity of the production were determined. To fulfill the required operations, the relevant machines and equipment were collected from different industrial applications. However, the selecting decisions were restricted to the technical information provided by vendors via inquiries and quotations. Therefore, further testing and trials with the actual materials will be required in future work in order to ensure the feasibility of the selected machinery. A capacity analysis was also implemented so as to examine the satisfactoriness of selected machinery, and also to determine the bottleneck when scaling up production. In the analysis, AnaRatio numbers were calculated by comparing the desired capacity with the actual capacity of the principal machine in each process. Two types of AnaRatio numbers were used, including buffering capability AnaRatio and processing capacity AnaRatio. Buffering capability AnaRatio numbers show that the bunker and the mixing tank have an adequate buffering capability so as to avoid disturbances in material supplying. However, the AnaRatio numbers of other machines indicate a low efficiency of machine utilization. It can therefore be deduced that the facility is able to increase its processing capacity. The analysis also determined that the dryer is a potential bottleneck of the system when increasing processing capacity. Based on the analysis, a suitable scaling factor can be obtained by verifying the bottleneck of the production.

The floor layout and 3D visualization successfully demonstrated the structure of the automated processes, as well as supporting the planning of space requirements and location for machinery and production areas. The flow of materials within the facility can be determined clearly via the layout of the machine and equipment. The layout also provides a sensible locating of logistic ports, dirty areas and clean areas, as well as efficient organizing the machinery and processes so as to minimize the movements of materials. From the floor layout, the required space for the pre-processing, rearing unit handling, and post-processing areas were obtained. Space calculation shows that space is effectively utilized with a total free area equal to 9.6 % of the total. This free area is considered sufficient for smooth and convenient traffic within production. 3D visualization of the facility was generated directly from the layout design using the Factory Design utility software package. This has provided a full view of machinery organizing and installation. However, the detail scenes also reveal several installation issues which influence production operations. Adding support equipment or executing better installation could overcome these issues.

A control system was proposed to integrate processes, machines, and equipment in order to establish a full automation system. Since the production processes mainly use discrete control, PLCs are selected as the hardware controllers for the processes. To support the maintenance and modification in the future, PLCs are distributed to processes. In the proposed system, the HVAC system, robot, automated forklift, and machines, which have in-built PLCs, are connected to the PLC controllers via an Ethernet network using the OPC UA standard. Other field machines and devices are connected to the PLC controllers via a Fieldbus network. The proposed control system has proven the feasibility and availability of technologies to develop an automation control system for production. However, the selection of communication protocols was not examined in this thesis and is still an open question for future development.

This thesis also presented IEC 61499 standard FBs for the development of automation software. The FBs were created from the state machines using nxtSTUDIO. The result consists of eight FBs to control eight sections in the production system. To create the FBs, basic type FBs and a composite FB were used. Basic type FBs were driven by ECCs which were derived from the state machine while the composite FB was created by composing basic FBs to integrate multiple control functions. Each created FB contains initialization events (INIT and INITO) to set the initial conditions to output signals and operating events (REQ and CNF) to generate output signals from inputs. The result shows that it is possible to implement modular automation control from the designed state machines using the IEC 61499 standard. However, the automation control software has not been programmed from the FBs and the FBs have not been verified with any simulation.

In conclusion, the thesis has proposed a development of automated processes for the production of Black Soldier Fly. A six-step strategy was presented, applying elements of industrial automation in order to automate production processes. The results successfully showed that the available technologies are feasible for the development of production automation. For further work, the selection of processing machines should be verified via testing and trials with actual production materials to fulfill the desired specifications. Future research could also develop the programming of automation software, and use simulation in order to improve the design of the automation of production.

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7 APPENDIX

7.1 Appendix: State machine

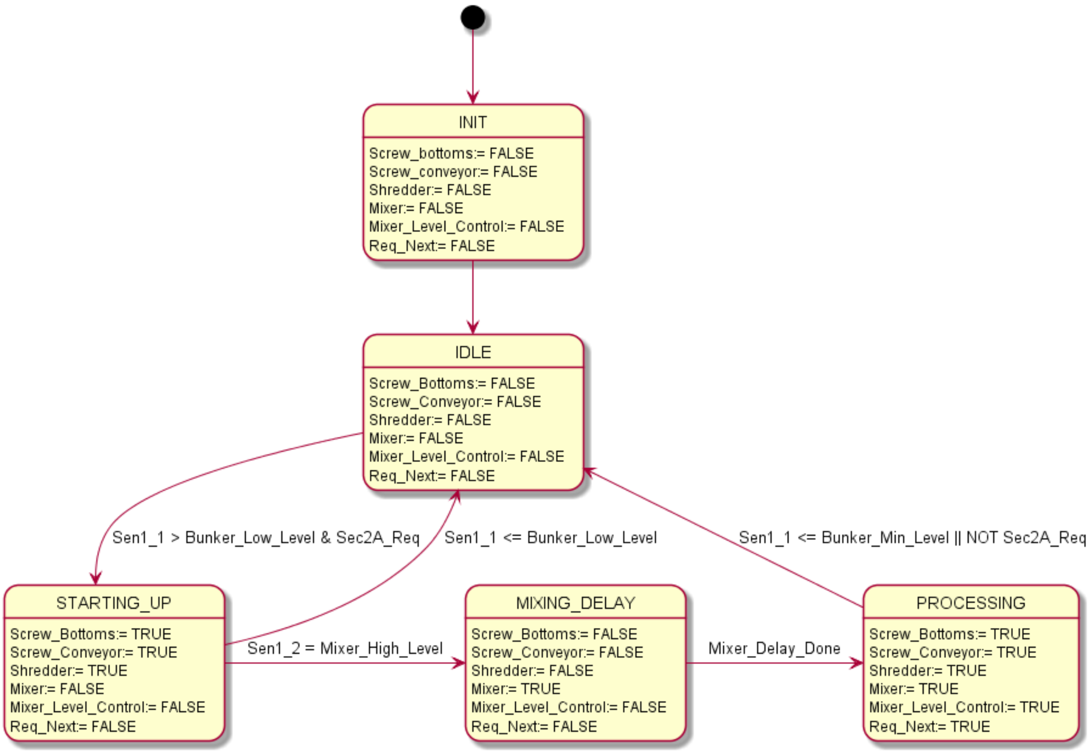

Figure 50: State machine for section 1

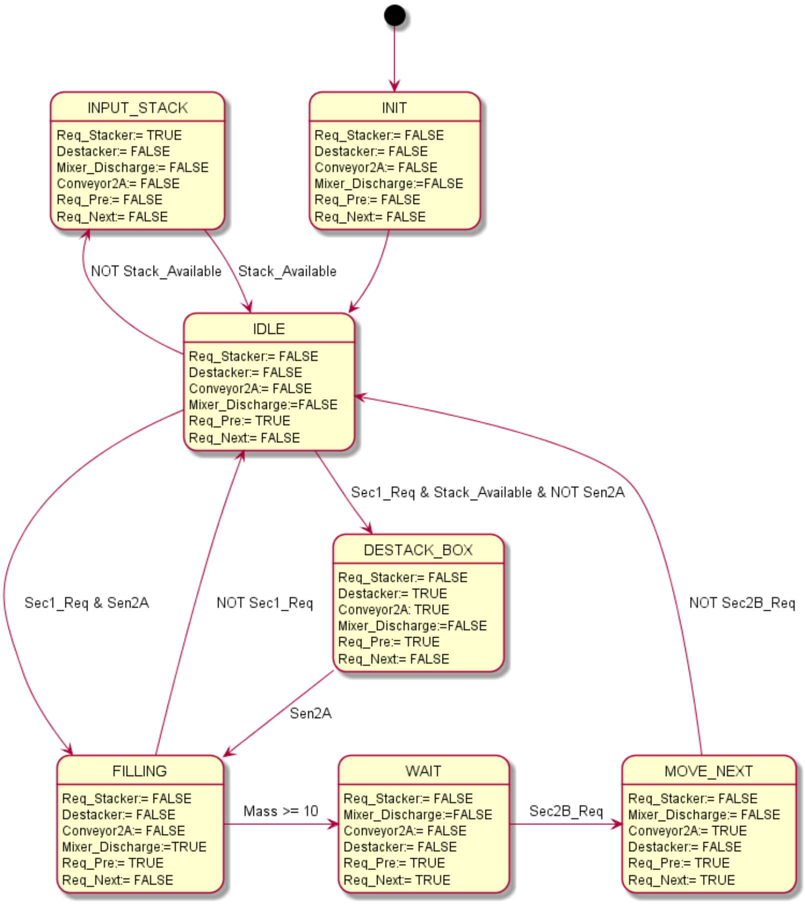

Figure 51: State machine for section 2A

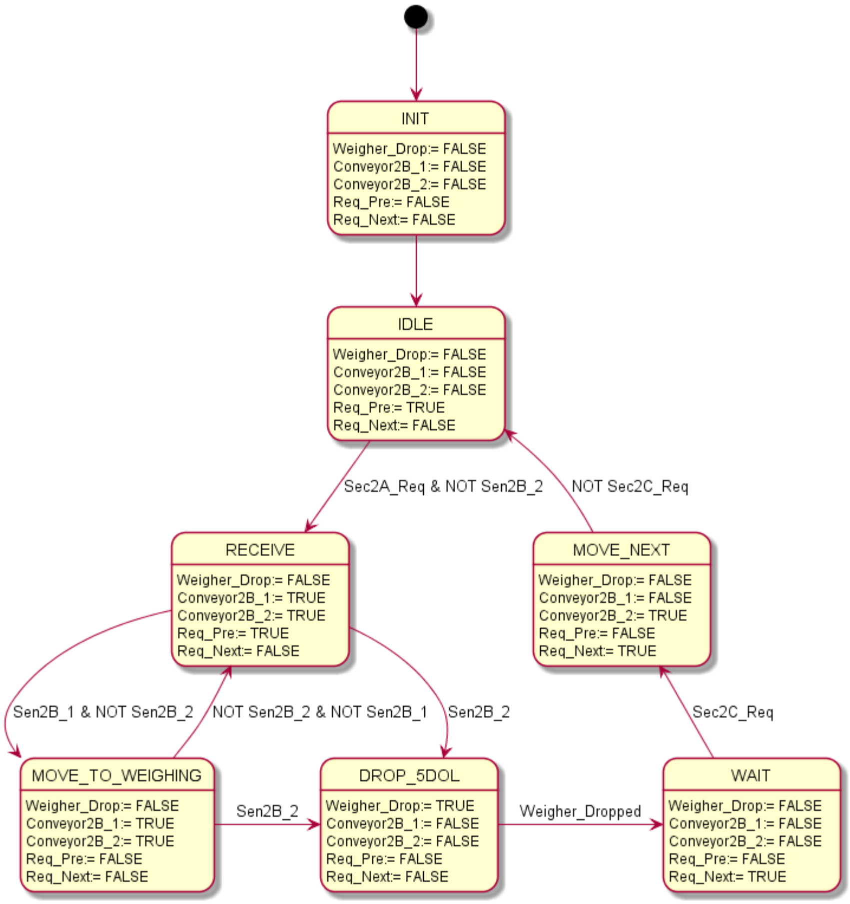

Figure 52: State machine for section 2B

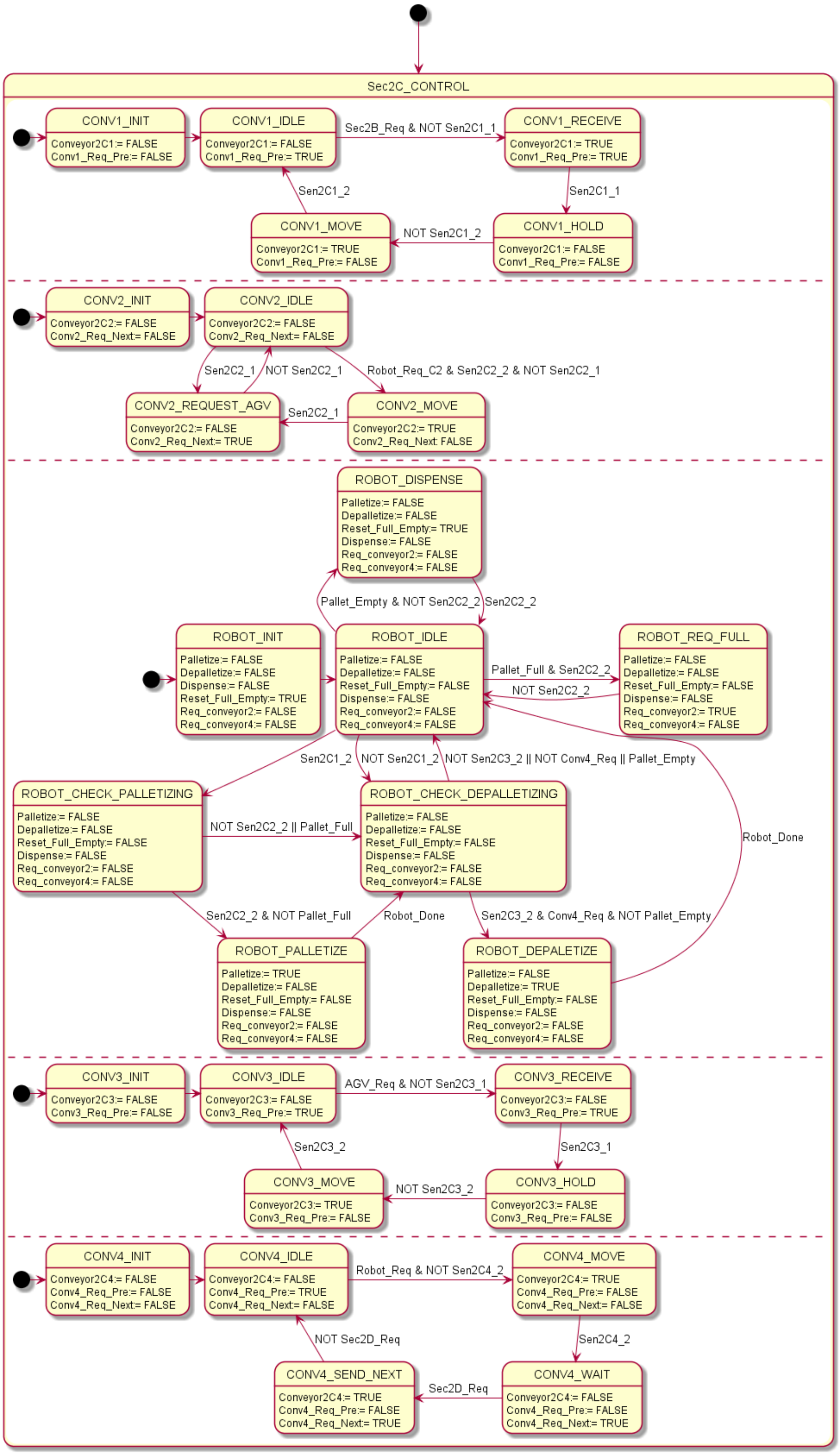

Figure 53: State machine for section 2C

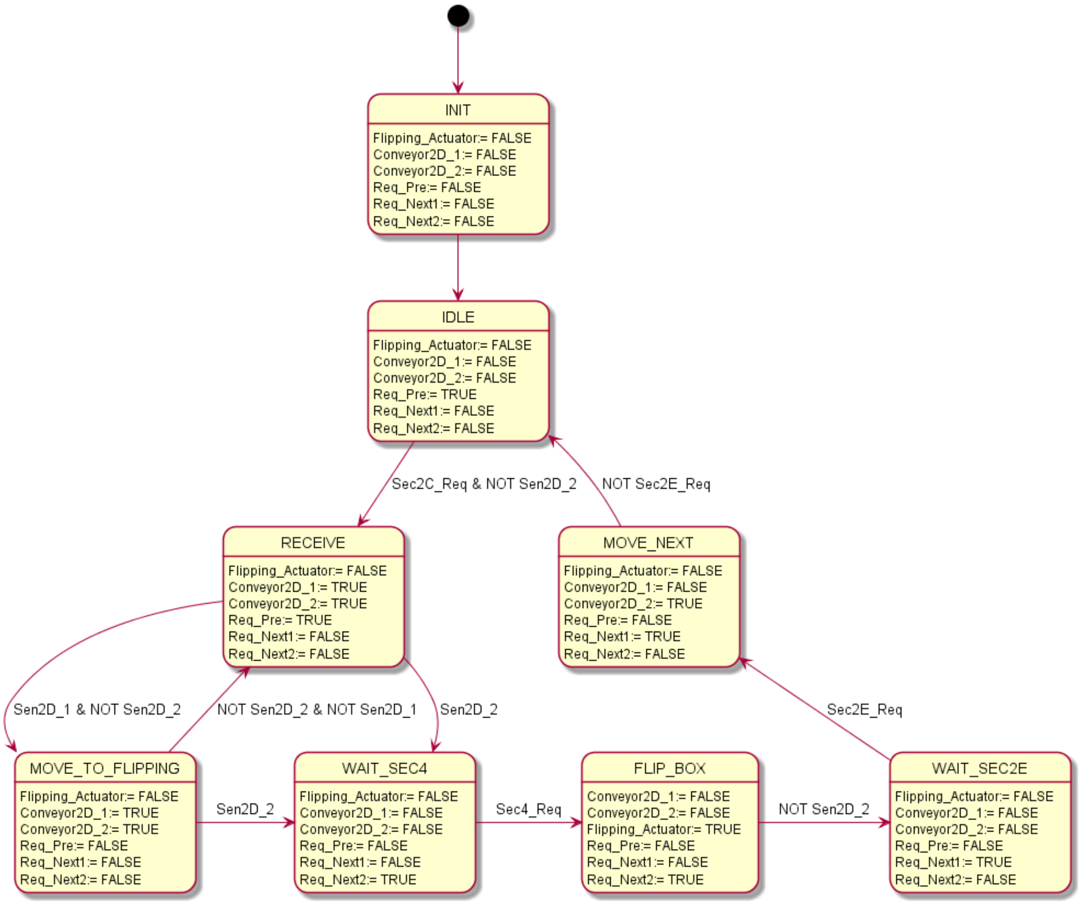

Figure 54: State machine for section 2D

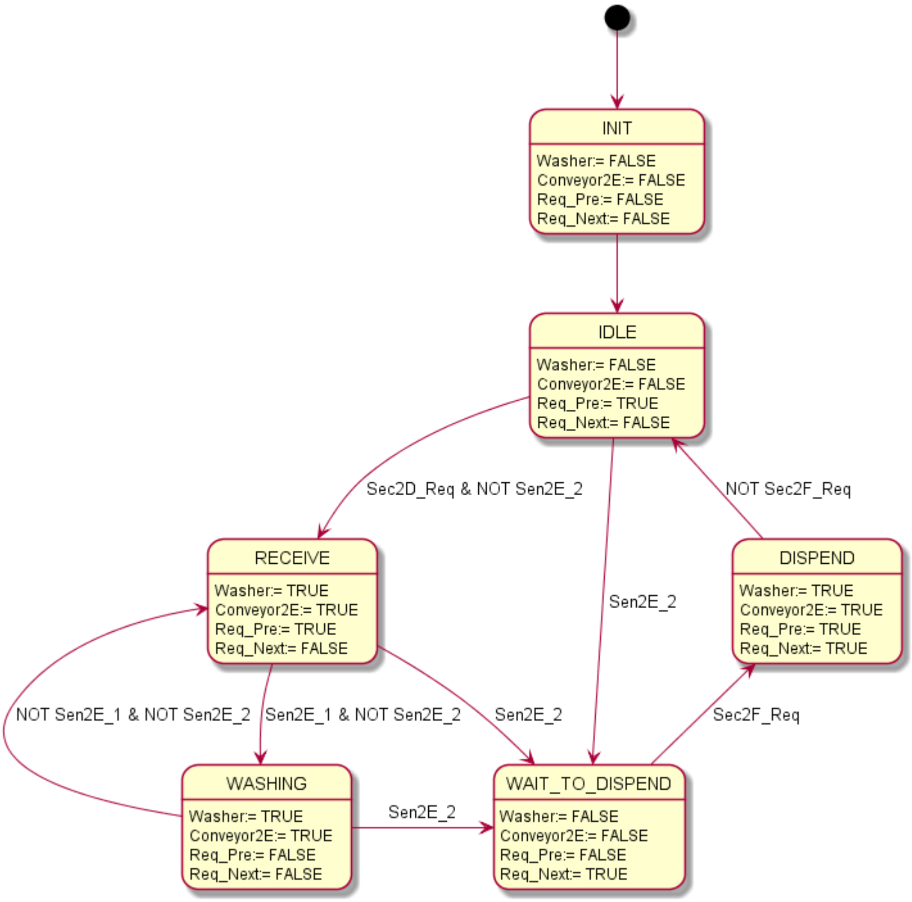

Figure 55: State machine for section 2E

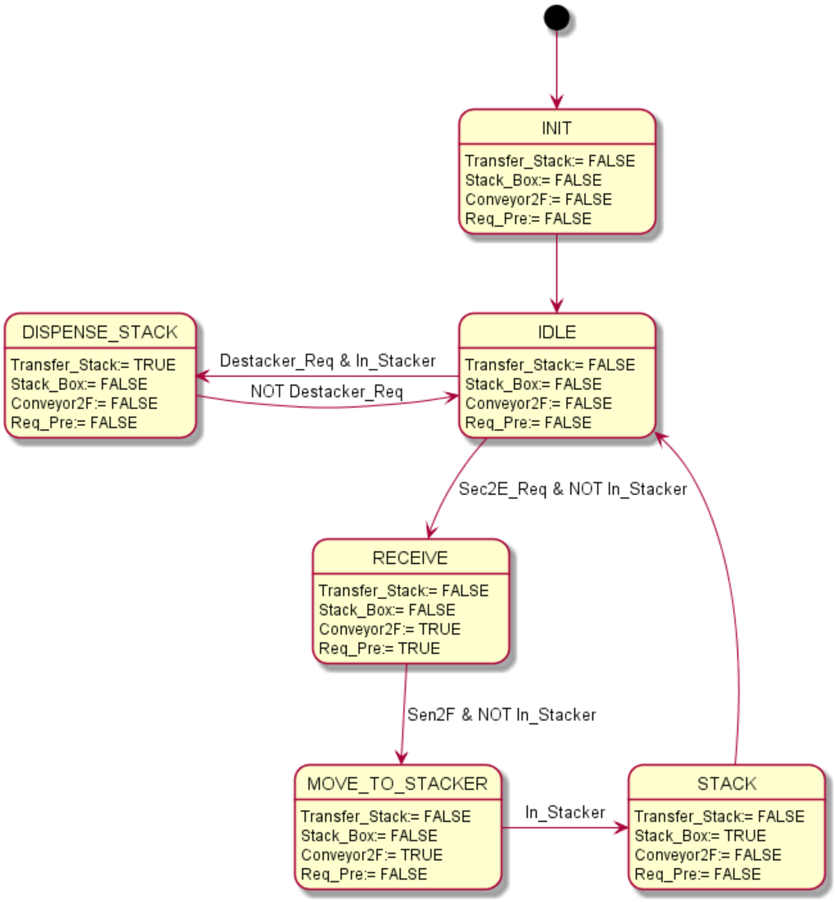

Figure 56: State machine for section 2F

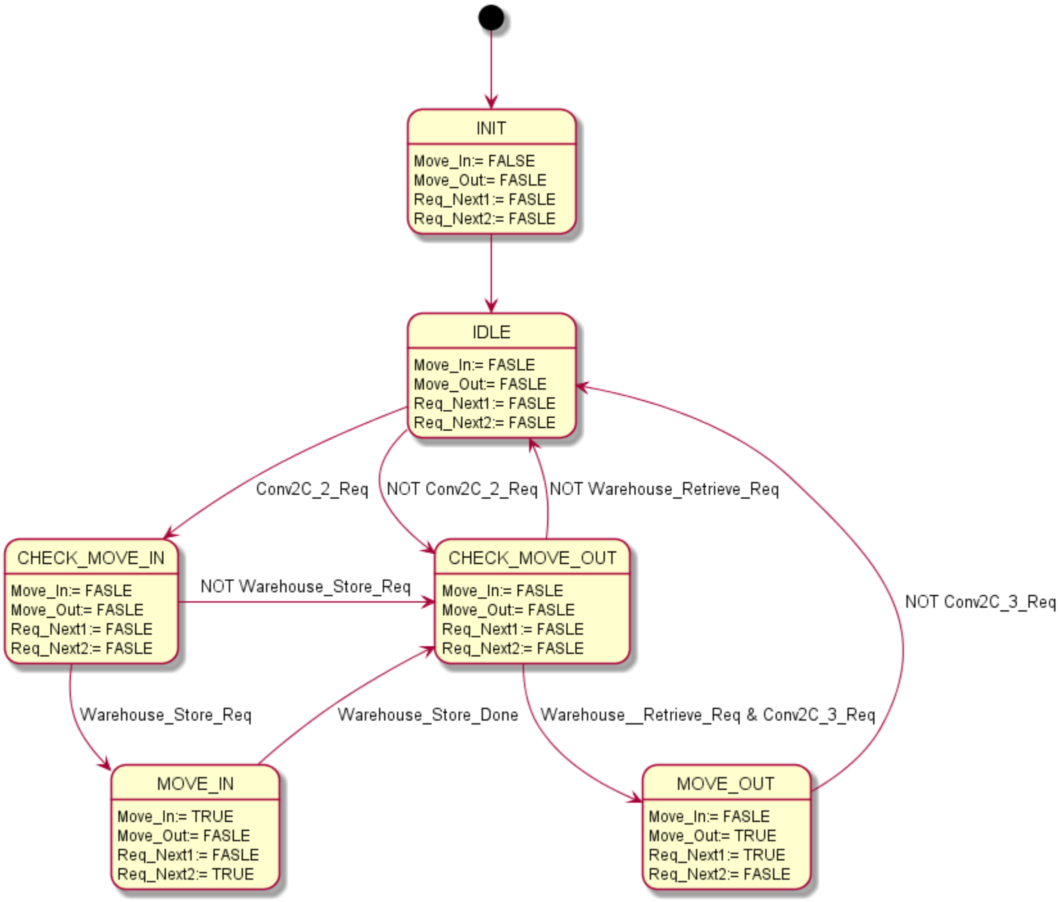

Figure 57: State machine for section 3 AGV

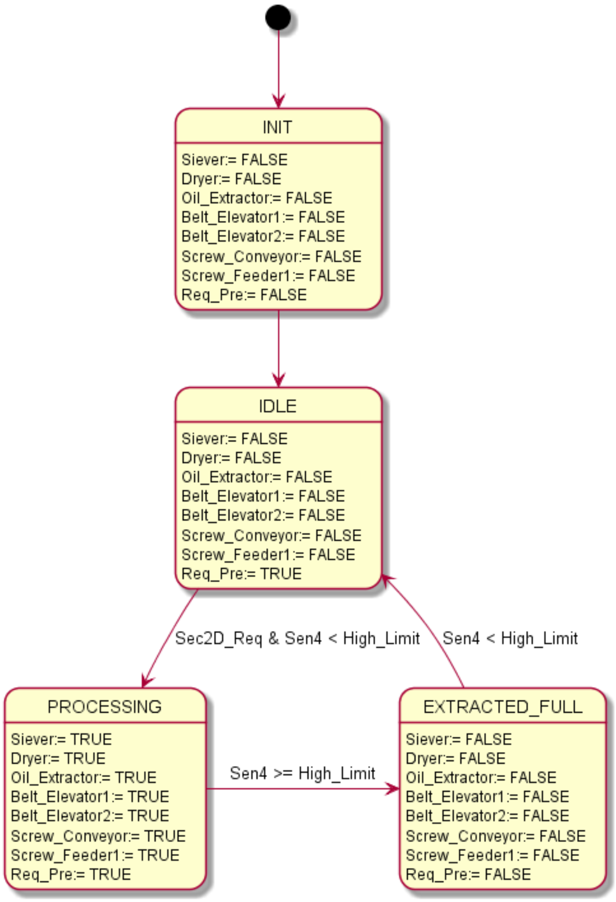

Figure 58: State machine for section 4

7.2 Appendix: Executed Control Charts (ECCs)

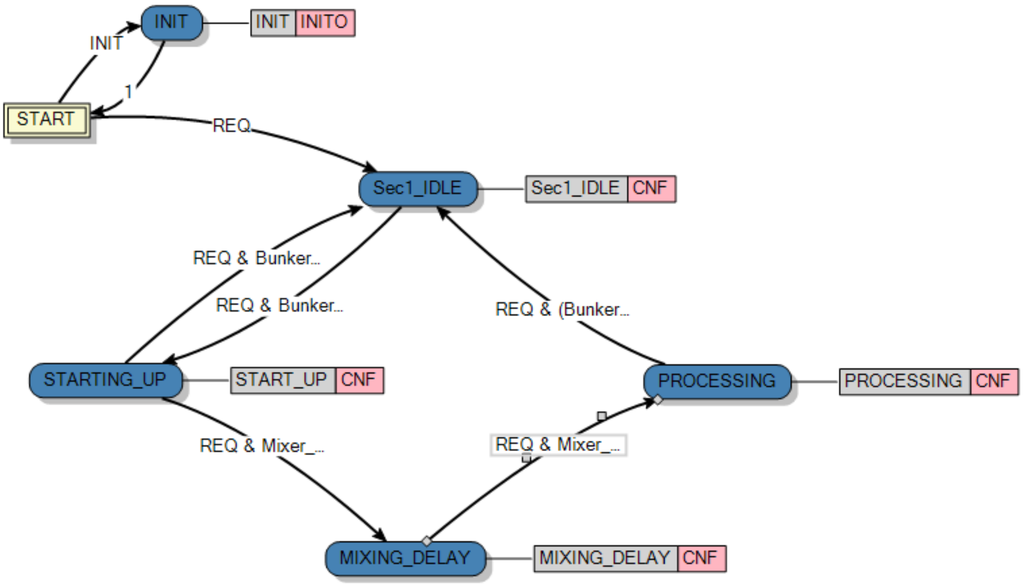

Figure 59: The ECC for section 1 control function block

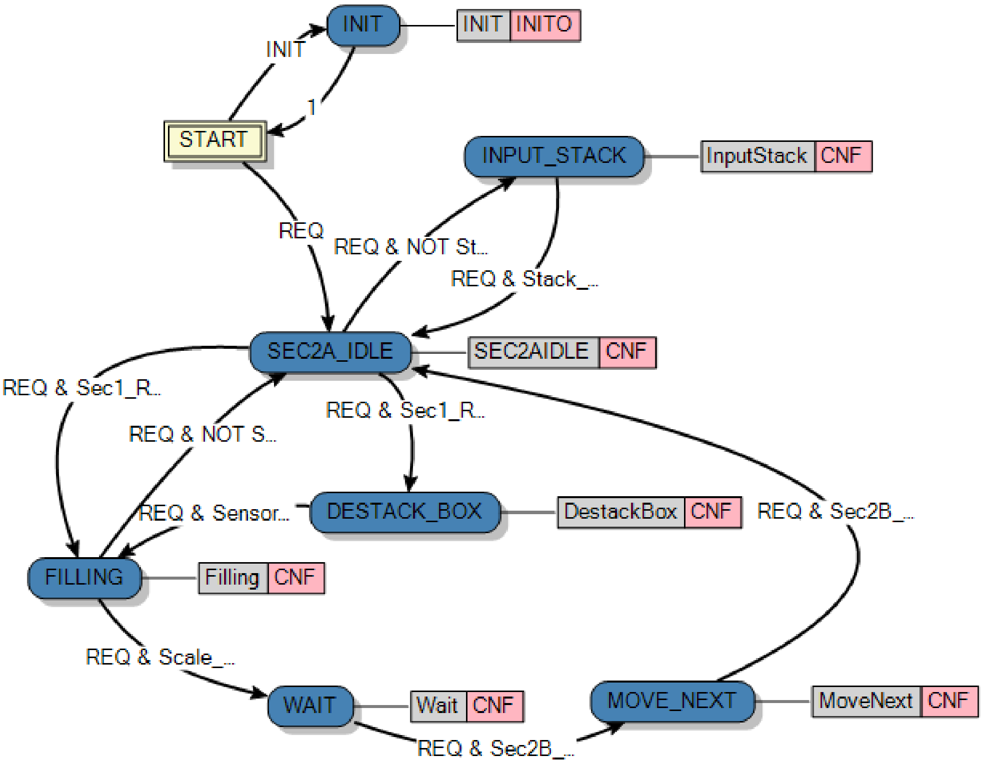

Figure 60: The ECC for section 2A control function block

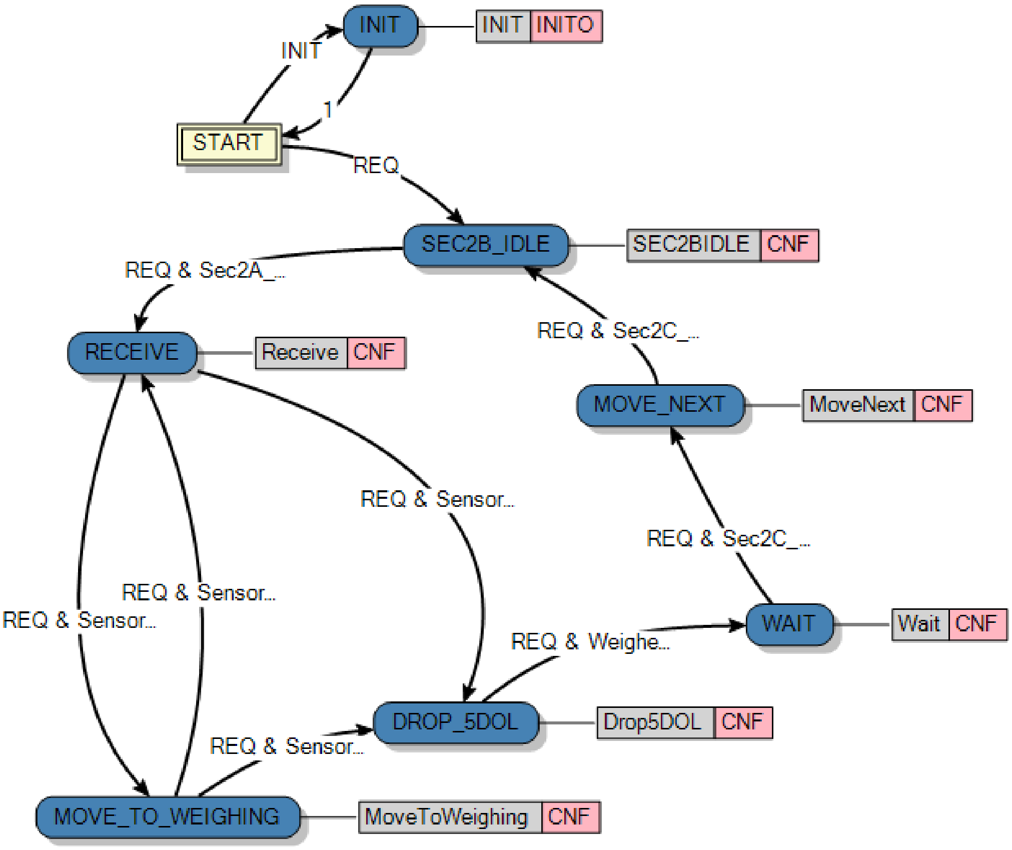

Figure 61: The ECC for section 2B control function block

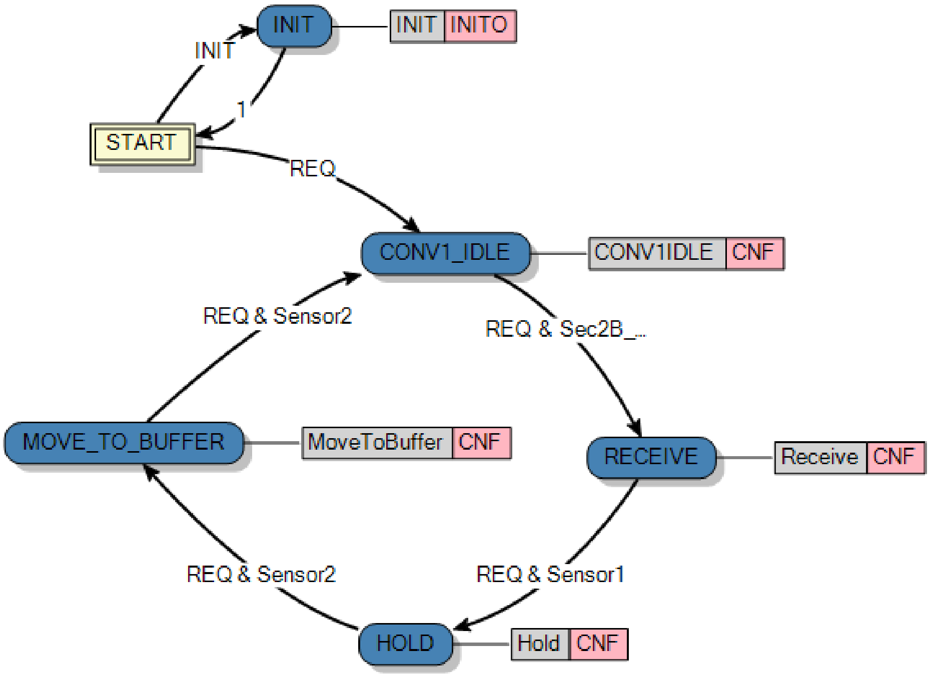

Figure 62: The ECC for the control function block of section 2C conveyor 1

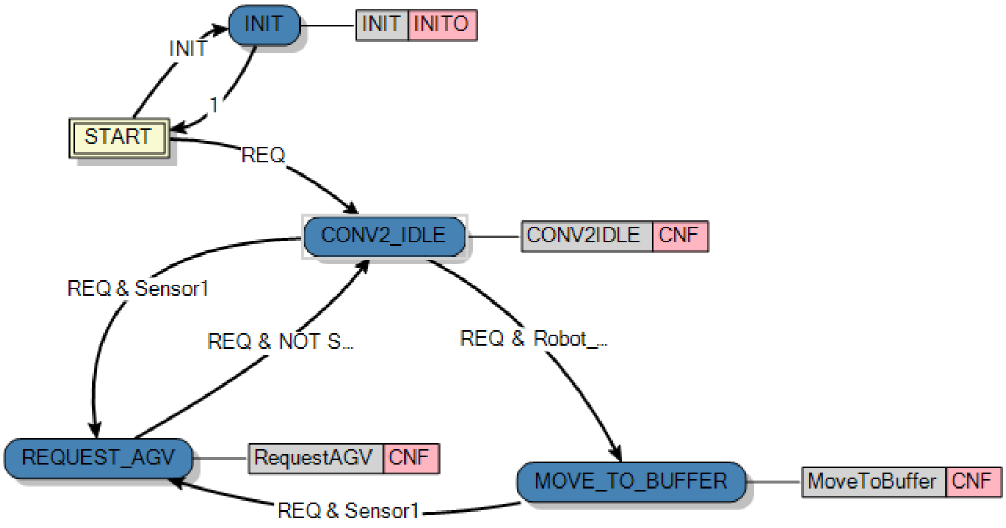

Figure 63: The ECC for the control function block of section 2C conveyor 2

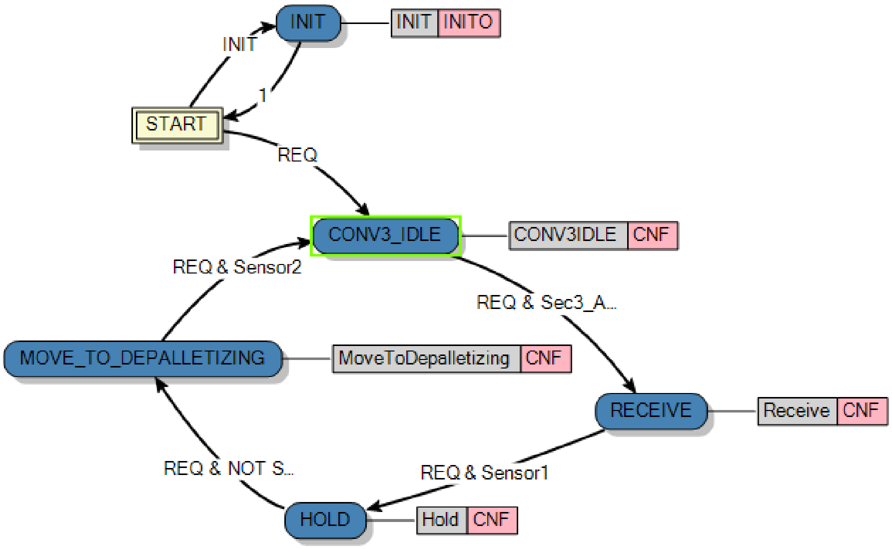

Figure 64: The ECC for the control function block of section 2C conveyor 3

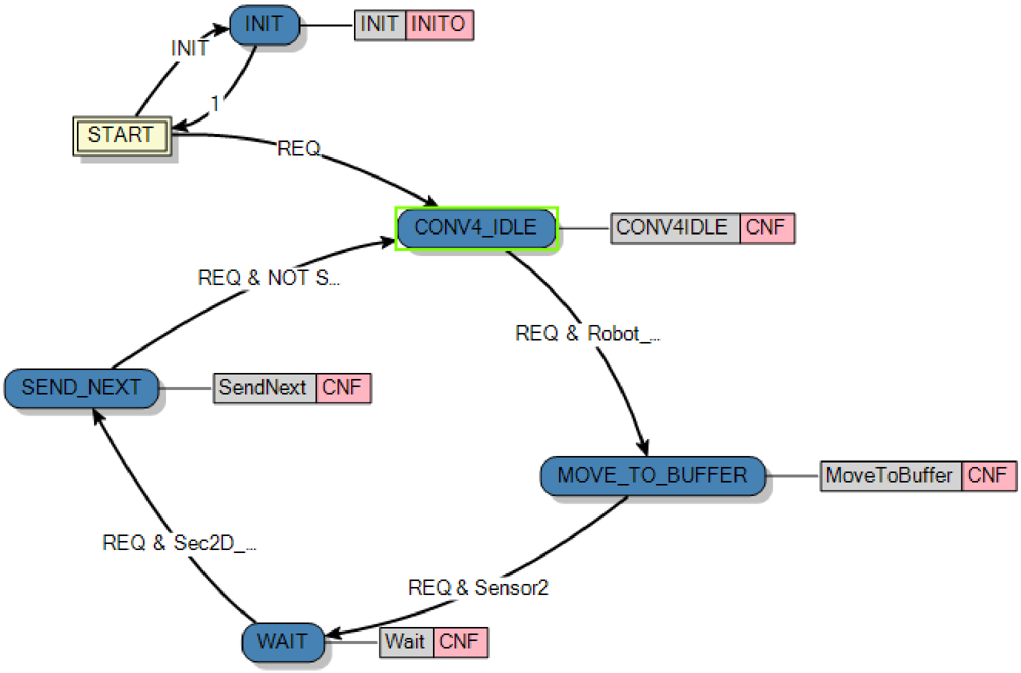

Figure 65: The ECC for the control function block of section 2C conveyor 4

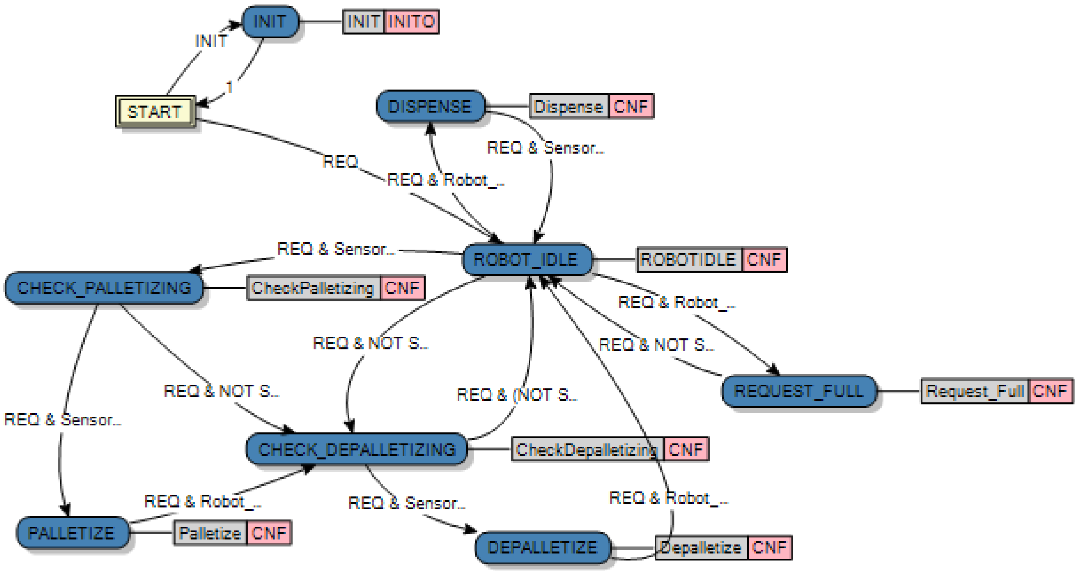

Figure 66: The ECC for the control function block of section 2C robot

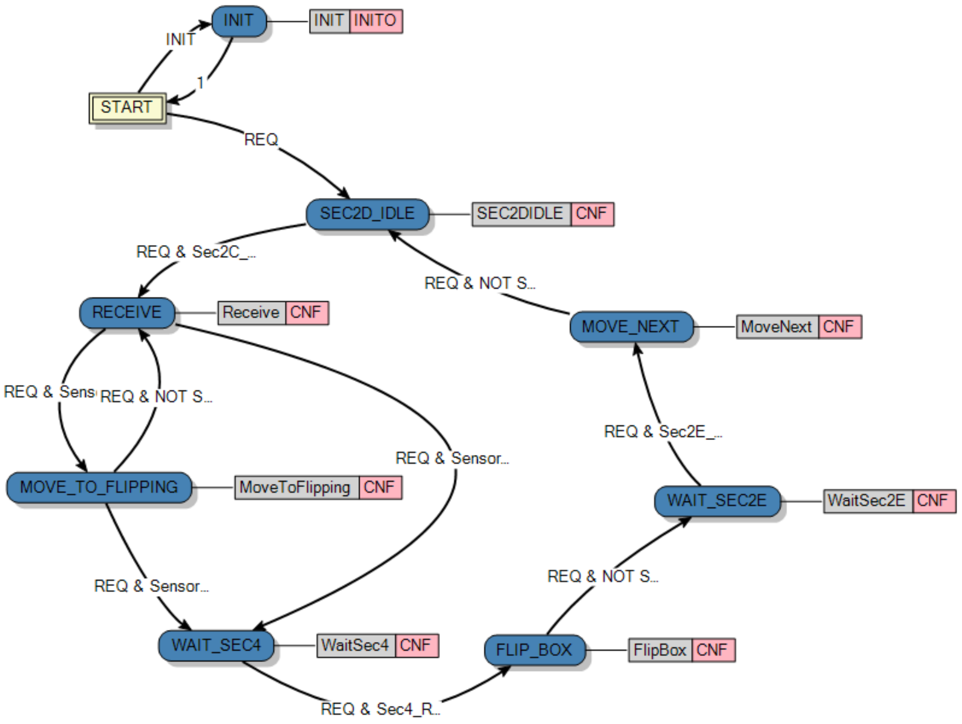

Figure 67: The ECC for section 2D control function block

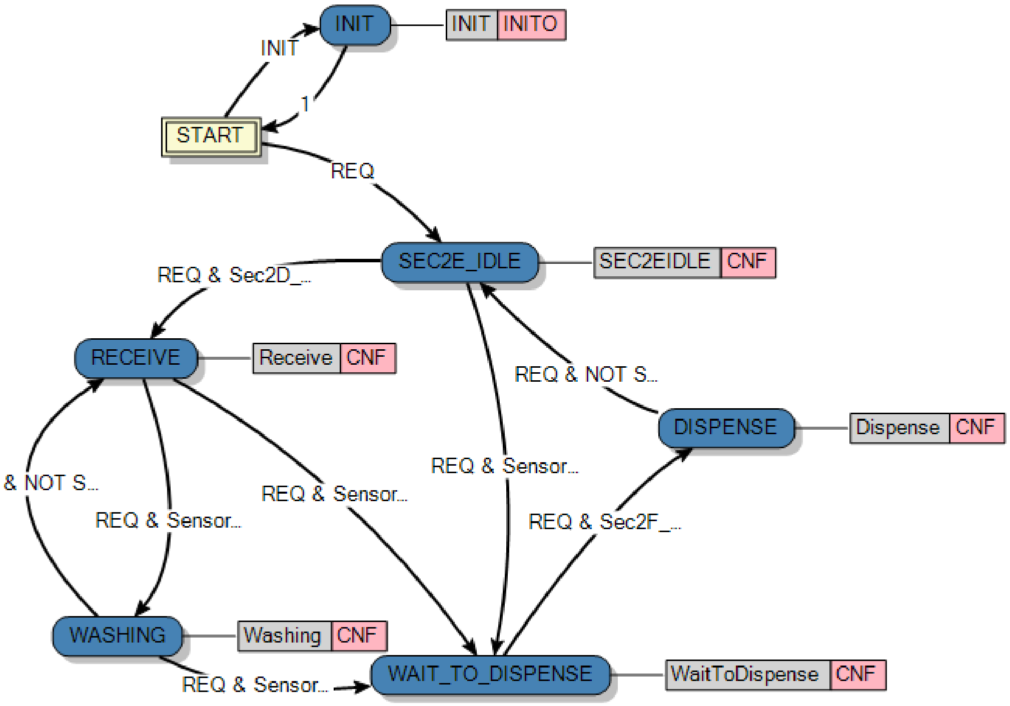

Figure 68: The ECC for section 2E control function block

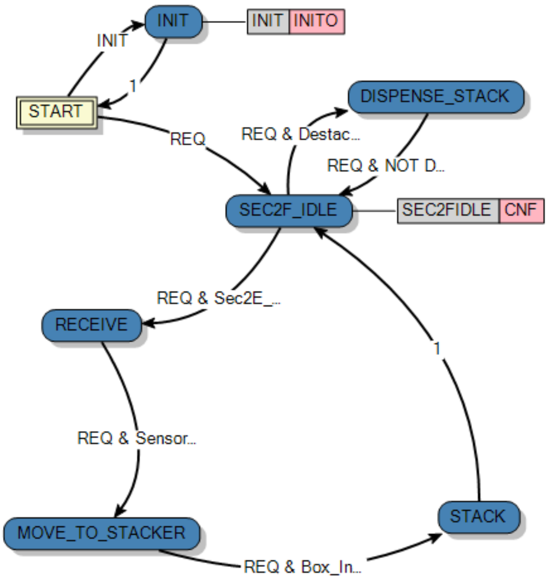

Figure 69: The ECC for section 2F control function block

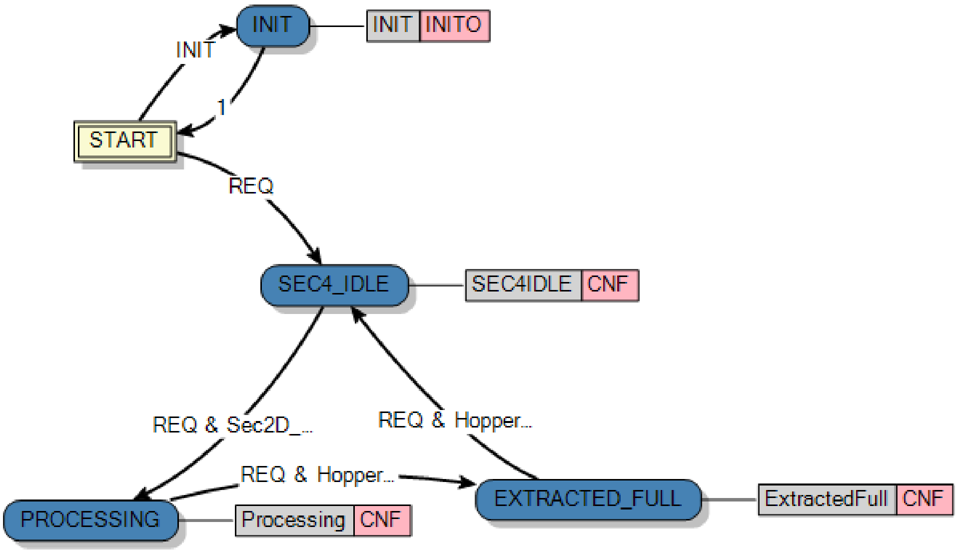

Figure 70: The ECC for section 4 control function block