INTELLIGENT CONTROL OF SCHEDULING AND VARIABLE FREQUENCY CONTROL OF PUMPS IN AN INDUSTRY PRODUCTION LINE

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INTELLIGENT CONTROL OF SCHEDULING AND VARIABLE FREQUENCY CONTROL OF PUMPS IN AN INDUSTRY PRODUCTION LINE

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LIST OF SYMBOLS AND ACRONYMS

Adjustable Speed Drives	the letter ASD
Agent-Oriented Programming	the letter AOP
Bottles per hour	the letter bph
Computer-Aided Engineering	the letter CAE
Computer-Aided Engineering	the letter CAE
Computer-Aided Manufacturing	the letter CAM
Differential Algebraic Equation	The letter DAE
Distributed Control Systems	the letter DCS
Expert System	the letter ES
Field Devices	the letter FD
Input / Output	the letter I/O
Internet of Things	the letter IoT
Liters per minute	the letter lpm
modelling and simulation	the letter M&S
Multi-Agent Systems	the letter MAS
Object-Oriented Programming	the letter OOP
Operating System	the letter OS
Ordinary Differential Equations	the letter ODE
Physical signal	the letter ps
Predictive Engineering Analytics	the letter PEA
Product Lifecycle Management	the letter PLM
Production Line	the letter PL

Programmable Logic Controller	the letter PLC
Pumping Station	the letter PS
Single Input Single Output	the letter SISO
Variable Frequency Driver	the letter VFD

SUMMARY

The soft drink manufacture is one of the non-alcoholic categories of beverage industry. The carbonated drink production line (PL) includes from water treatment to packing. The carbonated drink production line includes pump stations, has water treatment and drink mixers, CO_2 steel tanks, balanced pressure machines labeling and packing machines. This Thesis is focused on the automatic control of carbonated soft drinks production line operation based on Distributed Control Systems (DCS), in order to keep the tanks level control, and expand the line's production capabilities with cost-effective resource management that deliver optimal results across the supply chain. One of the basic control aims is the optimal speed control of the automatic carbonated soft drinks production line, in order to be adjusted infinitively and to accord with the standards.

This thesis has the following purposes:

(1) to examine the available state-of-the-art control methods that can be applied to a production line optimal management
(2) to study the structure and operation of action modern soft drink production lines (PLs) which include manufacturing and bottling production line,
(3) to design a Distributed Control Systems (DCS) for a standard soft drink PL in order to achieve tank level control, and safety operation
(4) to model, simulate and test a soft drink production line including hydraulics which consists of pump stations, tanks, valves, pipelines, speed controllers and the proposed Distributed Control Systems (DCS) system
(5) to design scenarios of the incorporation of Model based Predictive Control (MPC) in the proposed DCS system for a standard soft drink PL in order the optimal control management of the PL,
(6) to test the performance of the simulated soft drink PL for different operation situations under DCS control,
(7) to research upon all available simulation software able to handle large scale hydraulic plants and large scale water distribution networks systems.

The data and materials we use are similar to true ones from two modern existing soft drink companies, such as the Czech KOFOLA CeskoSlovensko AS and the Greek ETANAP-Samaria SA. The modeling and simulation of the pump station of a soft drink PL is implemented in Simulink of MATLAB®, using the Simscape Fluids™ (formerly SimHydraulics®) library, based on a time slicing approach.

The extracted simulation results of the three different simulated operational scenarios of our virtual PL and the simulated proposed DSC control system, verified that the proposed DSC is effective and appropriate. The first scenario represents the case study that simulates the normal, (nominal) operation of the PL, under the condition of stable flow (nominal manufacturing and the bottling process). The second scenario simulates a situation where one of the three pumps are malfunctioning. The last scenario simulates a situation where two of the three pumps are faulty. The DSC control system manages the first malfunction by scheduling and regulating the remaining pumps and stabilize the optimal flow at the operating range and terminates the system if another (second) malfunction occurred.

According to our simulations results, the automatic process control methods as DCS is necessary for soft drink PL.

Keywords: Model-based predictive control, Distributed control, Dynamic simulation, Multi-agent system, Variable frequency drive, Production line modeling, intelligent devices, pump station, hydraulic simulation, soft drink factory, MATLAB®, Simulink®, Simscape®.

ΠΕΡΙΛΗΨΗ

Η γραμμή παραγωγής ενός εργοστασίου αναψυκτικών ποτών περιέχει όλες τις διαδικασίες παραγωγής, από την επεξεργασία του νερού μέχρι την εμφιάλωση και συσκευασία των προϊόντων. Μια τέτοια γραμμή περιέχει αντλιοστάσια, δεξαμενές ανάδευσης για την επεξεργασία του νερού και των ποτών, δεξαμενές που περιέχουν CO_2 , μηχανές εμφιάλωσης καθώς επίσης ετικετοποίησης και συσκευασίας. Η εργασία εστιάζει στην ανάπτυξη συστήματων αυτόματου έλεγχου (automatic control) για γραμμή παραγωγής αναψυκτικών βασισμένη σε κατανεμημένα συστήματα ελέγχου (DCS), με στόχο τον έλεγχο της στάθμης των δεξαμενών και την αποδοτική διαχείριση των πόρων προσφέροντας αποτελέσματα σε όλη την γραμμή.

Οι στόχοι της εργασίας είναι:

(1) να εξετάσει τις διαθέσιμες σύγχρονες μεθόδους ελέγχου όπως κατανεμημένου ελέγχου (Distributed Control System – DCS), και προβλεπτικού ελέγχου (Model-based Predictive Control - MPC) σε γραμμές παραγωγής,

(2) η μελέτη της δομής και της λειτουργίας μια πραγματικής σύγχρονης γραμμής παραγωγής που περιλαμβάνει παραγωγή και εμφιάλωση ανθρακούχων αναψυκτικών ποτών,

(3) ο σχεδιασμός ενός κατανεμημένου συστήματος ελέγχου (DCS) για μια γραμμή παραγωγής αναψυκτικών προκειμένου να επιτευχθεί βέλτιστος έλεγχος της παραγωγής, ο έλεγχος της στάθμης των δεξαμενών και συγχρόνως να τηρούνται οι περιορισμοί λειτουργίας

(4) ο σχεδιασμός, η προσομοίωση και η μοντελοποίησης μιας γραμμής παραγωγής αναψυκτικών, που να προσομοιώνει το πλήρες υδραυλικού σύστημα (δεξαμενές, αντλιοστάσια, βαλβίδες, αγωγούς) και το κατανεμημένο σύστημα ελέγχου (DCS),

(5) ο σχεδιασμός σεναρίων τρόπων ενσωμάτωσης της μεθόδου Model based Predictive Control (MPC) στο προτεινόμενο κατανεμημένο σύστημα ελέγχου για την βέλτιστη διαχείριση μιας γραμμής παραγωγής,

(6) η δοκιμή και αξιολόγηση της αποτελεσματικότητας του προτεινόμενου συστήματος κατανεμημένου ελέγχου σε διαφορετικές καταστάσεις λειτουργίας της προσομοιωμένης γραμμής παραγωγής αναψυκτικών,

(7) η διερεύνηση των δυνατοτήτων του διαθέσιμου λογισμικού για την προσομοίωση μεγάλης κλίμακας υδραυλικών συστημάτων και συστημάτων διανομής νερού.

Σύμφωνα με τα αποτελέσματα των προσομοιώσεων αποδεικνύεται ότι ο κατανεμημένος έλεγχος DCS, είναι αποδοτικός στον έλεγχο και στην βελτιστοποίηση των μοντέρνων γραμμών παραγωγής ανθρακούχων ποτών και κατ’ επέκταση και σε εφαρμογές άλλων σχετικών τομέων της βιομηχανίας.

CHAPTER 1. THESIS PERSPECTIVE

In this thesis we focus on automatic process control and control engineering of the rapidly evolving industry of soft drink preparation and bottling production line (PL). Soft drink is typically a drink that it is contain carbonated water usually mixed fruits for example lemonade, orange soda and so the production chooses are countless. The soft drink industry has to deal with the complex production process of a large number of different products. The development of a reprogrammable and flexible production plant is really important and the use of intelligent control systems is essential. Moreover, the modeling and simulating of the production line and checking all details into a simulation tool to see how it behaves, many scenarios can be checked and monitored. The virtually building of a production line is expected to change the way manufacturers install new equipment.

There are only a few publications about the performance improvements optimizing a soft drink PL under the constraints of simultaneously energy efficiency and operation. There is a lack of studies for optimal control of a bottling line based on automatic process control implementations such Model Predictive Control (MPC), Distributed Control Systems (DCS) and Multi-Agent Systems (MAS).

It is our firm belief that the development of advanced control strategies like MPC approach, DCS and MAS have an important role on the production, factory and in general the soft drink industry's quality evolution. In general, automatic process control and control engineering are crucial parts of the production process and as the industries are moving towards the Internet of Things (IoT) such technologies will be developed even more.

One of the scopes of this Thesis is to create a virtual plant of a soft drink PL. The other scopes focus on the study of the application of Distributed Control System (DCS) and the incorporation of MPC control in a DCS or MAS approach on a soft drink PL. Until now, the above approaches, as DCS, MPS, MAS, are mainly used on manufacturing industries such as oil industries or wastewater applications for their production optimization and automatic process control.

The data and materials we use are similar to true ones from existing soft drink companies. During our personal visit to the Czech KOFOLA CeskoSlovensko AS and the Greek ETANAP-Samaria SA we had the opportunity to study the operation and the infrastructure of two modern soft drink bottling companies from Czech Republic and Greece. Analyzing the data from these two factories, we designed and simulated in detail a real soft drink bottling line which consists of a basic model of a soft drink PL including hydraulic behavior of pumps, valves, tanks, pump speed controllers and a distributed control system that manages the variable frequency drivers (VFD) of the pump station.

The modeling and simulation of the pump stations of a soft drink PL is implemented in Simulink of MATLAB®, using the Simscape Fluids™ (formerly SimHydraulics®) library, which is a programming environment with extensive availability of self-contained blocks of code that are far more easier to implement than traditional code (also, optimized for each specific task and simulation purpose, as well as readily available and licensed through our university). In order to compare the potential and the effectiveness of our proposed virtual plant, we further extended our research upon all available simulation software able to handle this specific or similar type of "hydraulic pump station" problems (i.e. Modelica®, OpenPlant®, Dymola®, to name a few) and large scale water distribution networks systems (i.e. EPANET).

1.1 Thesis outline

The literature survey is included in CHAPTER 2, which presents the basic information about advanced control methods which are being used in soft drink industries such as DCS, PID, PLC and MAS approaches as well as introduces the MPC method.

The CHAPTER 3 reviews the selected software simulation tool which is the Simscape Fluids™ (formerly SimHydraulics®) library of the model-based design environment of Simulink in MATLAB®. Also the chapter provides information about the tools and a review on research upon all available simulation software choices. Then, the data and materials which were collected from the research based on the two factories are presented in CHAPTER 4 and concludes on the basic production layout.

The CHAPTER 5 introduces the virtual design of the basic production layout and presents the individual modules-blocks which are included in the virtual soft drink PL plant. The simulated DCS control system is presented in CHAPTER 6 and consists of three simple controllers monitoring the flow rate of the water, syrup and bottling pipeline, three controllers which control the water, syrup and bottling pumping stations and valves over the production line as well as a control unit which monitors the state of the production's pipelines.

Then, CHAPTER 7 presents the simulation of three case studies which test the behavior of the virtual plant under different operation scenarios. First of all, the Scenario #1 simulates the functional behavior of the system where the virtual plant has normal (nominal) operation under the condition of stable flow (nominal manufacturing and the bottling process). The second scenario, Scenario #2: Malfunction of one simulates a situation where one of the three pumps are malfunctioning. The last scenario, Scenario #2: Malfunction of one simulates a situation where two of the three pumps are faulty.

Then, CHAPTER 8 describes three different design approaches of how MPC control can be included in a DCS control system of a soft drink production plant.

Finally, the conclusion of the thesis as well as the recommendations for further development of the research is presented in CHAPTER 9.

CHAPTER 2. LITERATURE SURVEY FOR INTELLIGENT CONTROL OF PRODUCTION LINE

This chapter presents the literature survey and includes a detail description of the research scope and the research approach literature as well as comparisons between the chosen approach and other methods that are the present state-of the art.

Soft drinks PL are by definition continuous production processes which process materials as an input and produces an end-product as an output. Automatic process control in continuous production processes is the a combination of control and chemical engineering which is used in industrial control systems to achieve production level of consistency, economic and safety which could not be achieved only with the use of human manual control. Furthermore, control engineering or control system engineering is a practice that applies on the automatic control theory to design systems with desired behaviors in a control environment.

2.1 The implementation of the DCS and MPC approaches

The production lines of soft drinks industry is based on automatic control for every production process. According to the papers [4] and Figure 2.1, a soft drink factory can be divided into five division, the first division consists of field devices such sensors and smart valves.

The next division consists of industrialized I/O modules and their distributed electronic processors – a more direct control. Generally, the distributed electronic processors are PID controllers or PLC microprocessors (see below), which are relative cost efficient, ease to apply and maintain, combined all together to compose a Distributed Control System (see below).

The next division contains the supervisory computers which collect information from the processor nodes on the system. Because they are distributed throughout the entire production line, they consist of a distributed control system.

The final two divisions are the plant supervisory and manufacturing/production control and scheduling. These divisions are crucial for the production line because they are monitoring and controlling every operation of the factory or PL and they are responsible for the efficiency and safety of the production.

Among the advanced control technologies, MPC (see paragraph 2.6) is a control method which is widely used in process industries because of its capability of dealing with complex systems such as soft drink factory. This is a hybrid approach on the process control where the use of MPC methodology is distributed throughout the entire system.

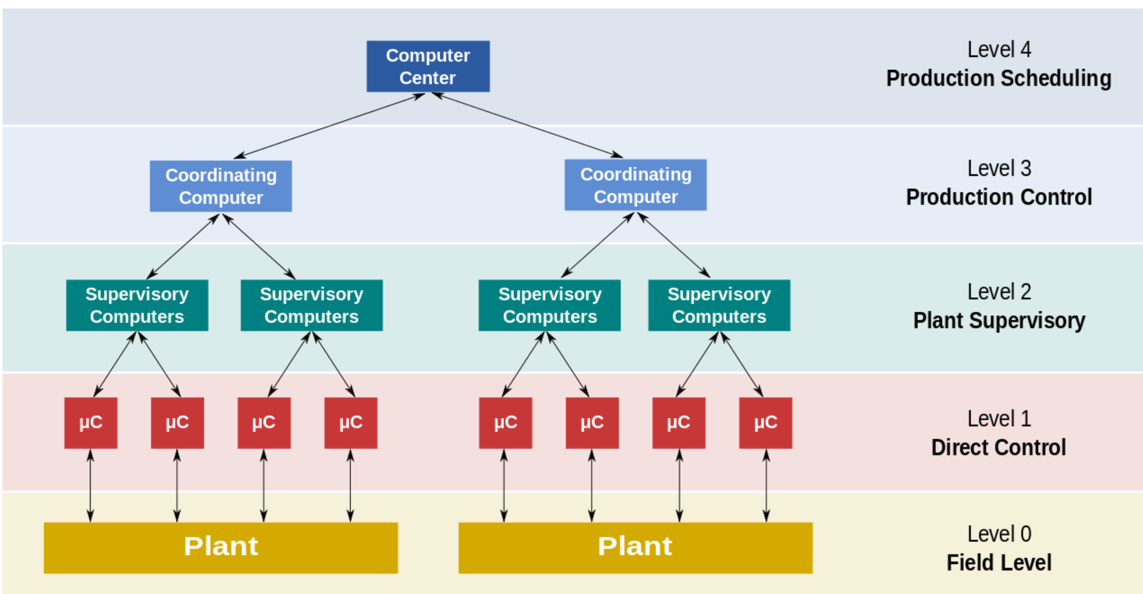


Figure 2.1 Functional divisions of a DCS

2.2 Intelligent control of the production line

The ever increasing demand for flexibility and reconfigurability of control systems in manufacturing and industries is an undisputable fact. Industries have and must adjust on ever changing modern market demands by producing smaller quantities of a wider range of products instead of mass production of a single one. That implies modularity and reconfigurability of the production machinery and the corresponding modularity of the software.

This idea is not new but it has been studied for many years as indicated in many publications [1]-[2]-[3]. For instance, concepts like dynamic control systems (DCS), supervisory control and data acquisition (SCADA), programmable logic controller (PLC) or model-based predictive control (MPC) are constantly being used and developed by industries.

2.3 Dynamic control systems

Nowadays, increasing demands on flexibility, reconfigurability, reliability, effectivity other and characteristics of industrial control systems initiate the control of the distributed components across the entire production plant.

2.3.1 Definition of DCS

Based on the papers [5]-[6]-[7]-[8], a general definition of DCS describe as it is a system consisting of several intelligent components which are cooperating and communicating with one another. So the term dynamic control system denotes of a control system, in our case study an industrial production line, in which the control components are distributed. As a result a communication network is used to monitor and control the production process. A DCS is commonly used in manufacturing equipment and utilizes input and output protocols to control the machine.

So it is easy to conclude the advantages of using DCS.

- DCS can handle complex control applications using dedicated controllers.
- Can be used in manufacturing of multiple products.
- DCS offers high reliability levels by maintaining system operation while the system still operates.
- DCS offers lots of predefine blocks and providing a large number of programming languages based on the engineer interest, making the programming of various control applications easer.
- DCS offers a sophisticated human machine interface (HMI) which provides sufficient data to engineers to change the system's behaviour.
- DCS offers a high level of scalability using big or small controller across the production plant.

2.3.2 Basic fundamentals of DCS

The DCSs are dedicated systems used to control manufacturing processes which are continuous such as soft drink manufacturing. They are connected with sensors and actuators and use setpoint controls to control the manufacturing process. In my case of study, the setpoint control loop consists of the controller, flow rate and pressure rate sensors, tank level, control valve and the pumping station. The measurements of the sensors are transmitted to the controller, using a ps to Simulink converter I/O device. When the measurement reach a certain point, the controller then regulates the system using the valves and pumping station depending on the conditions.

2.3.3 Basic elements of DCS

DCS is a systems consisting of distributed controllers that controls certain intelligent devices across the entire production plant. To fully understand the operation this subchapter is going to present the basic elements of a DCS based on the article [6].

The most important aspect of a DCS is the controller or the engineering PC which is the supervisory controller over the distributed controllers. The controller executes control algorithms and configures various device. Similarly there are the distributed controllers. As the name suggests, they are placed near to field devices. They receive instruction and parameters from the engineering PC and directly controls field devices. Next, there is an operating station which it is used to monitor the entire production plant parameters graphically (HMI), offering more effective display and easier monitoring. Lastly, there are the communication media and protocols. Communication media consists of wireless and wired networks like copper cables or fibre optic cables. Likewise, the communication protocols consists of the protocols used for the connection of various devices to the network.

2.3.4 Main differences between DCS and SCADA

Supervisory control and data acquisition or SCADA is an industrial control system (ICS) which is used for data gathering. Usually refers to centralized systems that control and monitor large complex systems which are spread out over large areas.

According to [9], the main difference between DCS and SCADA systems is that the first one is usually a process oriented in comparison to SCADA, which is data-gathering or event oriented. DCS concentrates on the control process while SCADA concentrates on the control centre and operators. SCADA main concern is the quality of the data that is shown to operator. Even though, it is commonly used on data gathering, it can be used for multiple process control.

Another outstanding difference between the two is that SCADA maintains a database of previous values, secure data and used them when the connection is slow and unreliable, making it fast for urgent operator display. On the other hand, DCS is always connected to its database as it is connected with all the intelligent components.

All things considered, despite the main differences, both systems come with the same standard facilities like event, archiving, HMI, reporting, database management and logging as well as control centre remote control. So the solutions that contained either one of them depend on the customer’s needs.

2.3.5 Main differences between DCS and PLC

PLC is the acronym for Programmable Logic Controller which is still used to control individual machines. Even though modern DCSs and PLCs are more similar than dissimilar based on the [10]-[11] there are some key differences.

Firstly, the main difference is that DCSs are used to control a factory or a production plant, when the PLCs are used to control individual machines. Secondly, PLCs have relatively simple operating system and their design to do simple task such as scanning and updating. The result of the simple OS structure is that the PLCs can manage programs faster, having very few background programs running on the processor. On the other hand, DCSs can control the entire system and processes at the same time. In this way, DCSs have a more complex OS structure because engineers expect them to provide a ready-to-use control system and features.

Lastly, DCS is used for high value manufacturing products which the production process is continuous and failures in the system results in damage to the equipment. DCSs offer redundancy, ensuring the system. All upgrades are made online without stopping the manufacturing process. While, PLCs are often used for manufacturing products with lower value and the production needs to be flexible. That is because the engineers had to shut down the manufacturing process for maintenance or upgrade the system.

2.4 DCS formal methods

According to the paper [12], there are many methods that implement the DCS concept, but there are formal methods that are more commonly used. In computer science, formal methods are a particular kind of mathematical techniques for specification, development and verification of a SW or HW system. To put it another way, there are methods that offers some advantages like the method can be verified for correctness by mathematical methods. Furthermore, engineers can used verified subsystems incorporated into larger system, knowing that they behave as specified and they can lead to a hierarchical semi-automated or even automated system development.

In general, formal methods of DCS have to satisfy some specific requirements related to formalism such as the modeling, verification, development and synthesis of the control system. In other words, engineers have to select the appropriate models and algorithms for sufficiently modeling the controller and system. Then, they have to verify the model by presenting with formal mathematical models of the system as well as the specification on how the controller should behave. Since engineers verified the specifications of the controller, they have to develop/construct a controller that the system satisfy them. In the end the controller, which was synthesized, is fully automated.

2.5 Agent based approach on a manufacturing process

Manufacturing design and control problems are particularly difficult because of the nature of the describing systems. Manufacturing systems are simulated on open, dynamic environment since things usually do not go as expected. For example, when the system is on manufacturing process of the soft drink, when ingredients like fruit flavored syrup mixed with soda water, is facing pressure loss because of a leak on the pipeline. Agent base technology has recently been considered as an important approach for resolving this kind of problems. In fact, agent concept represents an autonomous combination of HW and SW interacting with the environment. Additional, multi-agent system consists of multiple agents communicating all together in order to achieve a common task. Offering modular, scalable and flexible algorithms and systems solutions, a multi-agent architecture provides robustness and flexibility to a dynamic distributed system.

2.5.1 Definitions of basic agents

The Table 1 Definition of the basics agents presents the definition of the basics agents in agreement with the work [13] paragraph [1.1-1.7].

Table 1 Definition of the basics agents

Agent Type	***Definition***
Agent	A computer system capable of autonomous action in order to meet its design objectives.
Intelligent Agent	The agent which has the ability to adapt and learn through problem-solving-rules, algorithms or trial and-error-examples.
Agent-Oriented Programming	An agent construction approach, which is building agents and programming them using mental notions like beliefs, desire and intentions.
Autonomous Agent	A computer system which has the ability to act independently in the environment that is placed.
Artificial Intelligence	There are multiple types of agents and sub-agents both physical and temporal.

The last category of agents, based on Sepehri's work [13] paragraph [1.7], can be divide into five basic class based on their intelligence level and degree.

Table 2 Artificial Intelligent Agents

Artificial Intelligent Agents	***Definition***
Simple Reflex Agent	They can handle only observable environments, its function is based on if-condition rules.
Model-based Reflex Agent	Can handle partially observable environment, they stored their current state. This data structure describes the environment in which the agent is placed.

Goal-based Agent	A model-based agent which store information regarding the desirable situations. This feature allows the agent to choose among multiple possibilities, selecting one which will reach a goal state.
Utility-based Agents	A goal-based agent which can distinguish between goal and non-goal state by defining measurement of how desirable is a particular state using utility functions.
Learning Agent	An intelligent agent which can act independently, learning and adapting under different circumstances.

2.5.2 Differences between Agents and Objects

As reported in Sepehri's work [13] paragraph [1.8], objects and agents differ in several ways. There are two key areas that differentiate agent oriented and object oriented approaches are autonomy and interaction.

Table 3 Agents vs Objects

Difference	***Meaning***
Intelligence functionality	All agent and multi-agent systems are considered to be more functional (intelligent/ smarter).
Autonomous and reactive	Agents are autonomous and reactive because they can individually decide whether or not to respond to a message from other agents. Similarly, they are reactive since they are always listening and participating containing their own threading capability.
Communication language	Agents, especially intelligent agents, are using a powerful and complex agent communication language to communicate with each other. On the other hand, objects are using fixed set of messages in communication.

2.5.3 Differences between Agents and Expert Systems

Table 4 Agents vs Expert Systems

Agents	***Expert Systems (ES)***
Operates without the need for human interaction and it is capable of independent actions.	ES are been used for managing knowledge and expertise within a specific domain.
Agents share information, knowledge and tasks with each other. As result the capability of an agent system lies in the emergent behavior of the entire agent system not only on the intelligence of an individual one.	ES applications are found widely in business and government as ES development techniques and tool kits have multiplied.
Agents can learn and improve their performance in a dynamic environment.	
As they are autonomous and communicative entities, they present a more flexible and powerful alternative for conceptualizing complex problems.	

2.5.4 Multi-Agent Approach

Modelling and computation tasks are becoming much more complex as the size of the systems continuous to increase. As a result, it is difficult to handle using centralized methods. A good practise to this is the use of multi-agent systems (MASs). The major advantages of using MAS technologies are:

- individual agents take into account the specific nature and environment,
- local connections and interaction can be modelled and investigate and lastly
- MASs offer a good solution to distributed control.

In line with the papers [13]-[14], a MAS is defined as a system that consists of two or more agents, which cooperate with each other in order to solve problems that are beyond the individual capabilities. It is clear that a MAS design is more complicated that a single agent design. MASs support a modular, extensible approach to design of complex information system. They have been applied to various problems like monitoring, system diagnosis and remedial actions.

In general, agent-oriented programming (AOP) is the evolution of object-oriented programming (OOP), which integrates technologies in AI, parallel computing and telecommunications.

2.6 Introduction of the Model based Predictive Control (MPC) approach

To begin with, according to papers [15]-[16]-[17]-[18] MPC or model-based predictive control refers to a class of control algorithms that utilizes process model to predict the future response of the production plant. MPC presents an advanced control method which is used in process industries for dealing with complex systems. This approach does not define a control strategy but a set of control methods which take advantage of a mathematical model of the system to be controlled, in order to get the control signal, by minimizing a specific objective function.

So as claimed by Cataldo's work [17] MPC can have some basic concepts, such as:

- To predict the output at a future time instants (prediction horizon), MPC uses a mathematical method,
- Calculate the optimal control sequence by minimizing a specific objective function,
- Implementing the receding horizon strategy, at each time instant, the horizon is displaced to the future and only the first control signal of the optimal control sequence is applied at each step.

The success of MPC depends on having a reasonably accurate process models.

2.6.1 The implementation of the MPC approach

According to work [19], the MPC attempts to optimize future plant behavior by computing a sequence of future controlled inputs. The first is applied to the plant while the rest of the control sequence is ignored. This entire calculation is repeated at every sampling instant.

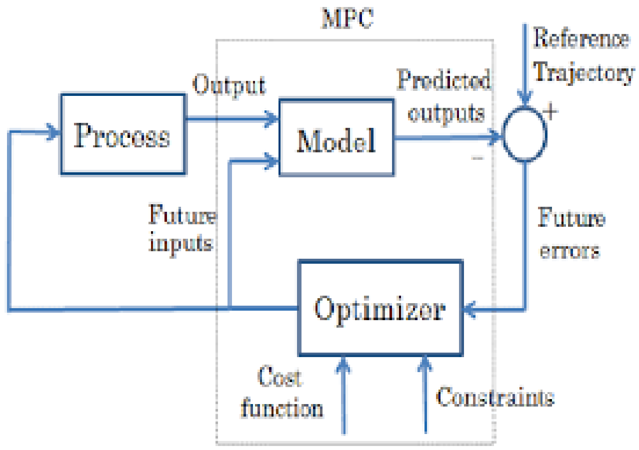


Figure 2.2 Basic structure of a MPC

As it is illustrated in Figure 2.2, the basic implementation structure of a MPC is presented. The implementation of MPC consists of an optimizer and a system model. The optimizer is fundamental part of the MPC because it offers the control actions or inputs. It is a mathematical function which optimizes the control signal by minimizing the cost function using the constraints. These control signals are send to system model and process as future inputs. The model is used to predict the future outputs based on past and current values send from the process and proposed future control inputs. The difference between the predictive outputs and reference trajectories is send to the optimizer which again optimize the future control signal. The key feature of MPC is to repeatedly solve an optimization problem based on the available measurements of the process current state.

2.6.2 Pros & Cons on the implementation of MPC approach

Considering all the above and based on the works [17] and ABB's research [18], MPC approach has many advantages over other control methods.

- It can used to control a wide range of processes, from simple to relative complex, including systems with long time delay or unstable,
- It increases the process knowledge, estimating hidden variables,
- It can handle a multi-variable cases,
- It can compensate the dead times,
- It uses feed forward control in a natural way to solve measurable disturbances
- It is an open methodology which allows for further development of the extensions,
- It offers higher level of automation, allowing operators to work on more important tasks,
- It provides an extended scope over the control strategy for optimization.

Nevertheless, the MPC approach has its drawbacks:

- The success of a model-based controller, like MPC, depends on having accurate process models. The design algorithm is based on prior knowledge of the system so it is affected by the variances between the model and the real process.
- The amount of computation required depends on the process dynamics and the constraints at every sampling time. So if the process dynamics do not change and the system is unconstrained, the derivations of the controller is done beforehand. However, on any other case, all computations have to be done at every sampling time.

CHAPTER 3. REVIEW OF AVAILABLE SIMULATION TOOLS FOR HYDRAULIC PLANTS

This chapter presents the Simscape Fluids™ library which enables to rapidly create hydraulic models of physical systems within the Simulink® environment. In general, with Simscape™, we build physical component models based on physical connections that directly integrate with block diagrams.

This chapter is a report for the capabilities of the chosen modeling and simulating software tools we use in the Thesis, in order to present the final conclusions that came out of our research and usage to the reader. Specifically, subchapter 3.1 presents the software tools and provides a report discussing the advantages and disadvantages. Subchapter 3.2 presents a list of the available software tools. Last but not least, subchapter 3.3 concludes based on the whole chapter.

3.1 Hydraulics in Simulink environment in MATLAB®

We use the software tool MATLAB® combined with the toolbox Simulink which is an additional environment and the library Simscape™. Although MATLAB® is intended primarily for numerical computing, with the addition of optional packages such as Simulink® it offers model-based designs and simulations. Simulink® is a block diagram environment for multi-domain simulation and Model-based design and it supports system-level design, simulation, automatic code generation and continuous test and verification of dynamic systems. More details are provided by Mathworks® *"Simulink User's Guide"* [22]. As a result, the engineers can simulate a rather complex system with specialized modules and functions. This is rather important for us, because the user can create distributed control systems using "intelligent control" multi-agent and MPC approach like the one presented in this thesis. An example of modeling and simulating a pump station is shown in Figure 3.1.

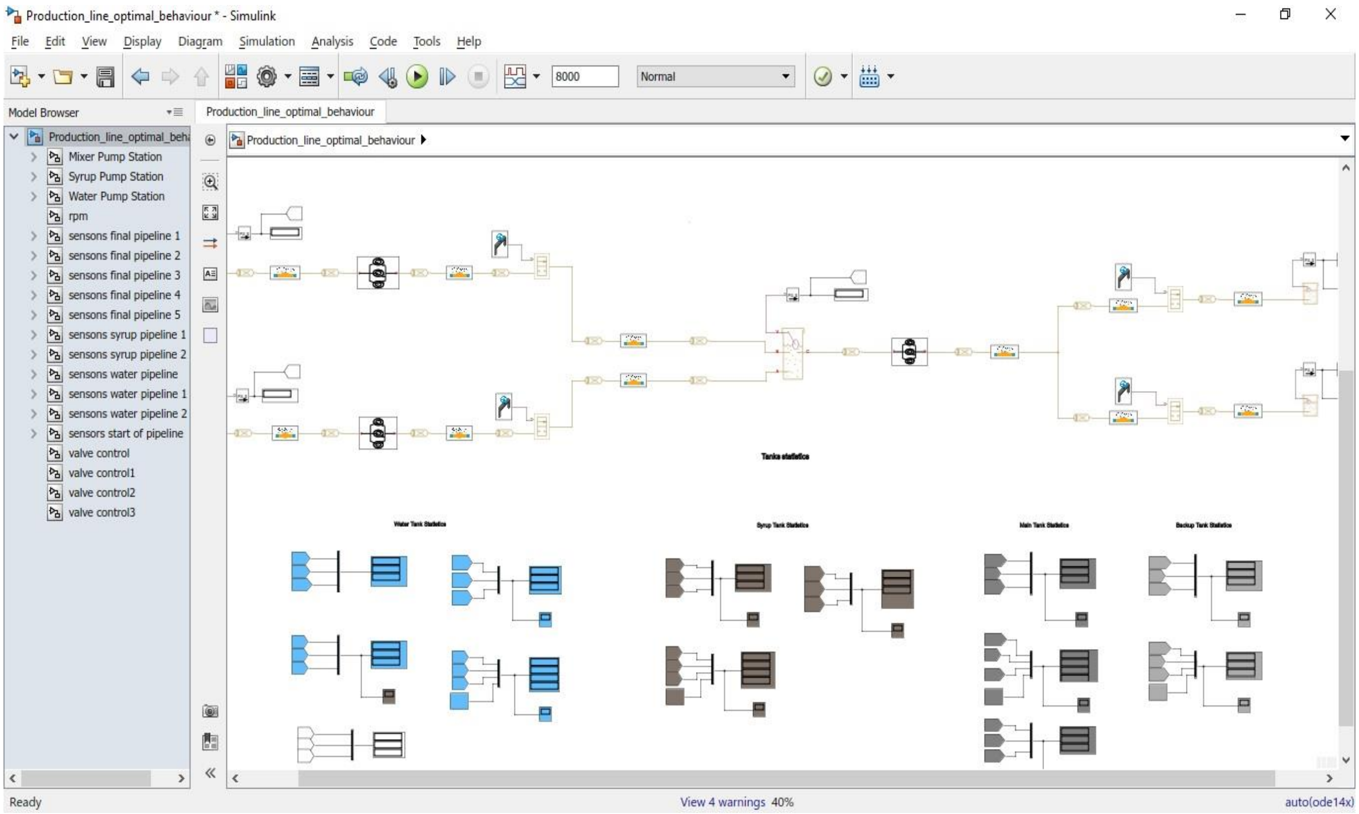


Figure 3.1 Simulink® GUI workspace. Simulation of a pump station of a production line.

3.1.1 *Simscape Fluids™ Review*

Simulink® provides a big library of toolboxes including the Simscape™ package that it's been used in our simulation. Simscape™ includes electronic, mechanical and hydraulic blocks allowing the graphic design and simulation of several dynamic system like a pump station of a soft drink production line. Simscape Fluids™ (formerly SimHydraulics®) provides component libraries for modeling and simulating fluid systems. It includes models of hydraulic pumps, valves, actuators, pipelines, and heat exchangers. Simscape Fluids helps you develop control systems and test system-level performance. We can parameterize our models using MATLAB® variables and expressions, and design control systems for your hydraulic system in Simulink®. This whole library of toolboxes and the fluids capabilities are clearly exhibited in Figure 3.2.

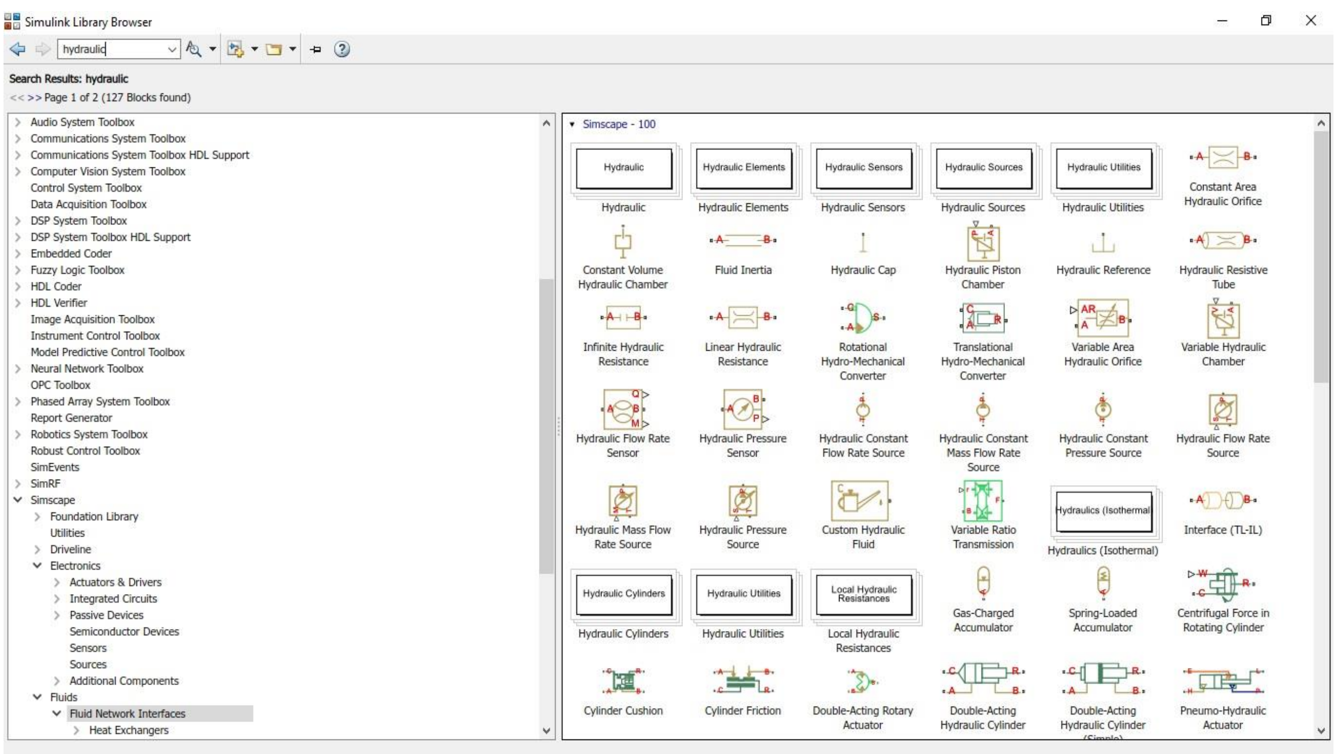


Figure 3.2 Simulink® Simscape Fluids™ Library capabilities.

3.2 Available simulation software review for large-scale water distribution networks systems (WDS)

The lack of more complicated and specialized blocks of Simulink® leaves room for research into more appropriate tools. Having that said, in this sub-chapter will present recommend additional software tools more specialized on modelling and simulating small, or large-scale water distribution networks systems (WDS).

Over the last several decades, system designers have recognized that the use of modeling and simulation can significantly reduce the resources necessary for exploring and analyzing the space of system alternatives. As a result, modeling and simulation of fluid power systems also has grown significantly in popularity and capability. Several dynamic simulation tools for fluid power systems have been developed both in academia [25]-[26] and commercially [27]-[28]-[29]-[30].

3.2.1 Numerical Convergence problems in Hydraulic simulations

The modelling and simulation (M&S) framework for small, or large-scale water distribution networks systems (WDS) uses a mathematical representation of its nonlinear dynamics and offers a better understanding of the system behavior. Subsequently, such an enhanced understanding enables potential improvements to WDS operation and/or design. The steady-state simulation is achieved by solving a set of hydraulic equations that include the mass and energy conservation principles. Many methods are developed for solving these equations.

The majority of water networks analysis methods and simulators are based on a *time slicing* approaches i.e. numerical methods, used in computer simulation of a system characterized by differential equations (e.g. tank dynamics), require the system to be approximated by discrete quantities. The solution of difference equation is calculated at fixed points in time. This feature of mapping a discrete time set to a continuous state set made the discrete time approach to simulation applicable in many fields including water networks analysis.

It is assumed that, in extended-period simulation (EPS) of water networks, the system is in a steady state between successive time stamps. But in fact, a real WDS continually adjusts itself in response to changing requirements of the users. This rises an important issue about the model fidelity of hydraulic behavior of a real WDS. Especially a WDS with pumps operation based on the water level in tanks, as if the time interval is not appropriate the events that actually happened in the real water network might be overlooked. It is evident that length of the time interval effects significantly the hydraulic simulation results. Furthermore, some elements included in a WDS model may cause numerical difficulties as convergence problems in simulation due to their inherent non-smooth and discontinuous characteristics.

For example, serious convergence problems may be encountered when simulating in Epanet2 a complex and large-scale WDS consisting of hundreds of elements. This is mainly due to the fact that switching events may not happen at the pre-selected time steps and then additional intermediate time steps need to be introduced. Such an approach is used in the water network simulator Epanet2 which introduces the intermediate steps when simulating water network models containing control elements. For example, serious convergence problems may be encountered when simulating in Epanet2 a complex and large-scale WDS consisting of hundreds of elements. This is mainly due to the fact that switching events may not happen at the pre-selected time steps and then additional intermediate time steps need to be introduced. In order to perform a more accurate state calculation an approach based on a discrete event solution can be used.

3.2.2 Discrete-event specification formalism (DEVS)

DEVS is a modular and hierarchical formalism, introduced by Zeigler (1976), for modelling discrete-event systems. DEVS can represents systems whose input/output behavior can be described by sequence of events with the condition that the state has a finite number of changes in any finite interval of time. A DEVS model processes an input event trajectory and based on that trajectory and its own initial conditions, it produces an output event trajectory. Furthermore, many extensions and modification to DEVS were proposed over the years. DEVS uses two types of structures to describe a discrete event system:

(i) atomic models describe behavior of elementary components whereas

(ii) coupled models describe collections of interacting elementary components.

The main advantage of the DEVS formalism is that atomic models can be coupled in a hierarchical way i.e. the coupled model could be defined as a set of atomic or coupled models. Therefore even complex structure can be modelled as a coupled structure of simpler ones.

Considering water network modelling the network elements such as pipes, valves, pumps could be defined as atomic models or coupled models forming a coupled model. Beside the hierarchical construction of the models and well defined concept of coupling of components another important feature of the DEVS formalism is its ability to simulate large and complex models in an efficient way. Hence, each atomic model has a corresponding DEVS simulator and a DEVS coordinator corresponds to each coupled model. At the top of the hierarchy, a root coordinator is in charge to control the progress of the simulation. Figure 3.3 illustrates such a mapping.

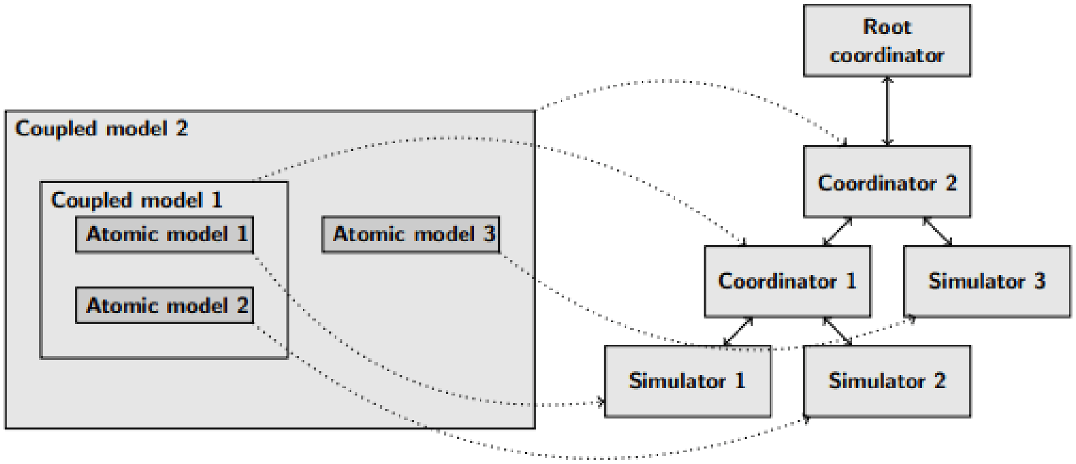


Figure 3.3 Mapping a hierarchical DEVS model onto a hierarchical simulator source by work [31]"Advanced modelling and simulation of water distribution systems with discontinuous control elements"

3.2.3 WaterGEMS® by Bentley

WaterGEMS® is CAD software tool that provides the engineers with a comprehensive yet easy-to-use decision-support tool for water distribution network systems (WDS). The software is capable of pipelines and valves analysis, build and management of hydraulic models to optimize the design of complex water distribution systems as well as to simulate networks in real-time.

3.2.4 LabVIEW® by NI

LabVIEW® is a systems engineering software for developing application that requires test, measurements and control. It based on the graphical language named "G" and helps the engineers to design every aspect of the system. It offers many libraries with a large number of functions for data acquisition, signal generation, mathematics, signal conditioning, analysis. In addition, it includes a text-based programming component named MathScript which provides with added functions for signal processing, analysis and mathematics.

3.2.5 Simcenter Amesim® by Siemens

Simcenter Amesim® is an integrated software platform that provides accurately model, simulate, analyse and predict the performance of intelligent systems. Models are described using non-linear time-dependent analytical equations that represent the system's hydraulic, pneumatic, thermal, electric or mechanical behaviour. Simcenter Amesim is based on the Bond graph theory and its libraries are written in C language with the additional support of Modelica language which is used to model complex physical systems. Lastly, it provides engineers and analysts with a comprehensive solution for development of complex products such as smart systems, implementing a PEA approach.

3.2.6 Simsen® by EPFL

Simsen® is a simulation software, developed by EPFL, for the analysis of electrical power networks, adjustable speed drives and hydraulic systems. It provides graphical I/O, modular structure and a wide range of ASD, electrical power and hydraulic component libraries. Another feature of SIMSEN is its open structure which allows newly developed units to be easily implemented. It is thus possible to widen the applications field furthermore in the future.

3.2.7 SimulationX® by ESI

SimulationX® is a CAD, CAM, CAE software tool, for design, simulation and analyse technical systems, based on Modelica (see subchapter 3.2.10). It offers various libraries corresponding physical domains as well as more specific application and industries including signal blocks, mechanics, power transmission, electrical and electronic engineering, fluid power as well as thermodynamics. Modelica-based and custom-build libraries can also be integrated into SimulationX. The models are created based on a basis of discrete network approach which means that the system is classified into logical sub-systems.

3.2.8 Dymola® by Modelon_

Dymola® is a CAE software application for designing and developing technical systems, based on Modelica (see subchapter 3.2.10). Large and complex systems are composed as component models providing a multi-engineering capabilities consisting of components from many engineering domains and describing the dynamic behaviour by mathematical equations and algorithms. It offers a comprehensive suite of Modelica-based libraries, providing system models for a wide range of industries such as automotive, aerospace, industrial equipment, energy and process.

3.2.9 CATIA® Systems by Dassault Systèmes

CATIA® is a multi-platform software suit for CAD, CAE, CAM and PLM. It supports multiple stages of product development (CAx) and provides the collaboration of a wide range of engineering domains through its 3DEXPERIENCE platform such as electrical, fluid and electronic design, mechanical and system engineering. CATIA® can be applied to a wide number of industries like aerospace and defence, automotive and industrial equipment to plant design, process power and petroleum.

3.2.10 Modelica by Modelica Association

Modelica is a free modelling language object-oriented modeling language for modeling technical systems in order to offer a standardized format. Except from that, it provides an open-source library which is offering a wide range of generic models, functions and packages. It is used for component-oriented modeling of complex systems such as mechanical, electrical, electronic, control, hydraulic, thermal, power or process-oriented subcomponents.

3.2.11 OpenModelica® by Linköping University

OpenModelica is an open-source modelling language Modelica-based modelling and simulation platform facilitates the description of large and complex systems for industrial and academic usage. It used in the fields of power plant optimization, automotive and water treatment. Like all Modelica-based software tools, OpenModelica utilizes Modelica Libraries and so it provides a large number of engineering domains. Models can be described in a hierarchical and modular fashion, interconnecting components similarly to the topological structure of the real system. These features along with extensive the Modelica libraries provide several modelling formalisms and ability to develop multi-domain models. An OpenModelica version is 1.9.1Beta2. Figure 3.4 shows a tank example in Modelica.

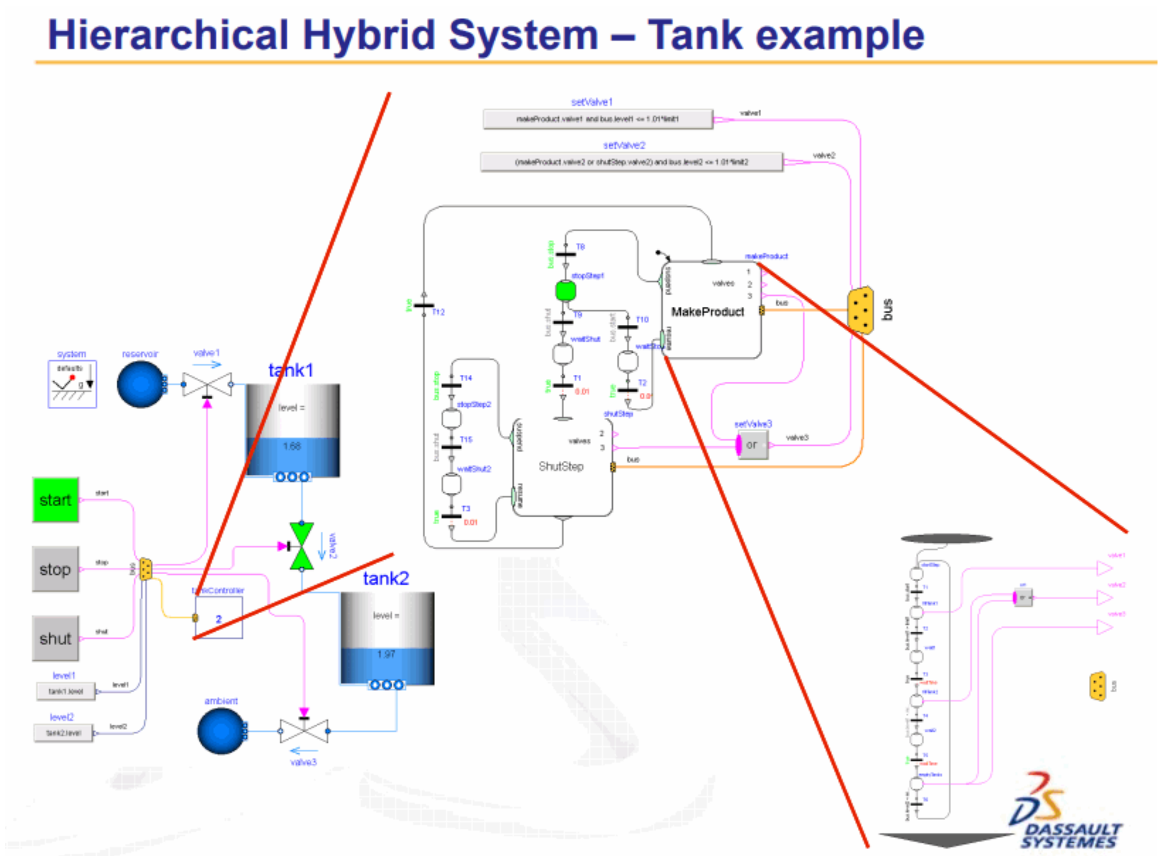


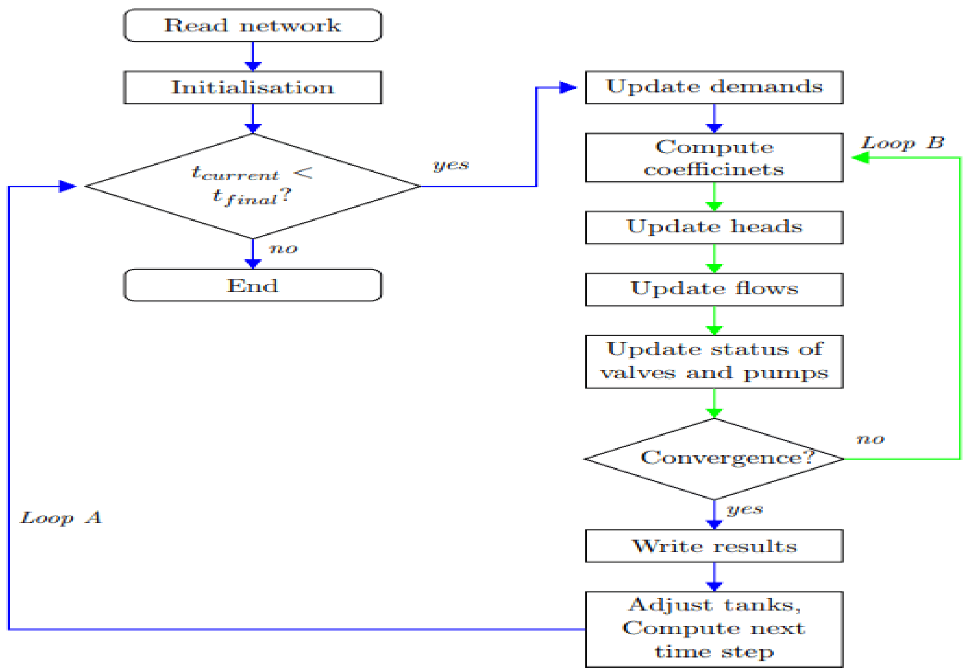
Figure 3.4 OpenModelica simulation of a tank

OpenModelica provides a number of methods for numerical integration (i.e. DASSL, IDA, EULER, IMPEULER) and simultaneous DAEs solvers (i.e. Newton method).

3.2.12 EPANET®

Epanet2 (Rossman, 2000b) is one of the most recognised water network solver in the water distribution research area. EPANET is software that models drinking water distribution piping systems. It is public domain software that may be freely copied and distributed. It is a Windows 95/98/NT/XP program.

EPANET performs extended period simulation of the water movement and quality behavior within pressurized pipe networks. Pipe networks consist of pipes, nodes (junctions), pumps, valves, and storage tanks or reservoirs. It allows water flow tracking in each pipe, the pressure at each node, the height of the water in each tank, the type of chemical concentration throughout the network during a simulation period, the age of the water, and source tracing. EPANET provides Euler method for numerical integration and simultaneous Newton method for DAEs solvers. Epanet2 is based on the gradient method by Todini and Pilati (1987).



Hydraulic simulation routine in Epanet2. Adapted from (Alonso *et al.*, 2000).

Figure 3.5 EPANET simulation routine (Alonso et al 2000)

Its simulation routine is shown in Figure 3.5. The routine contains two main loops; Loop A simulates the water network model over a desired period of time while Loop B is responsible for solving the system of non-linear equations.

EPANET Capabilities:

- EPANET's Windows user interface provides a visual network editor that simplifies the process of building piping network models and editing their properties and data. EPANET provides an integrated computer environment for editing input data. Various data reporting and visualization tools are used to assist in interpreting the results of a network analysis, including color-coded network maps, data tables, energy usage, reaction, calibration, time series graphs, and profile and contour plots.

- EPANET's fully equipped, extended-period hydraulic analysis package can do the following:
- Simulate systems of any size
- Compute friction head loss using the Hazen-Williams, the Darcy Weisbach, or the Chezy-Manning formula
- Include minor head losses for bends, fittings, etc.
- Model constant or variable speed pumps
- Compute pumping energy and cost
- Model various types of valves, including shutoff, check, pressure regulating, and flow control
- Account for any shape storage tanks (i.e., surface area can vary with height)
- Consider multiple demand categories at nodes, each with its own pattern of time variation
- Model pressure-dependent flow issuing from sprinkler heads
- Base system operation on simple tank level, timer controls or complex rule-based controls

EPANET Applications:

EPANET helps water utilities maintain and improve the quality of water delivered to consumers. It can be used for the following:

- Design sampling programs
- Study disinfectant loss and by product formations
- Conduct consumer exposure assessments
- Evaluate alternative strategies for improving water quality
- Modify pumping and tank filling/emptying schedules to reduce water age
- Use booster disinfection stations at key locations to maintain target residuals
- Plan and improve a system's hydraulic performance
- Assist with pipe, pump, and valve placement and sizing
- Energy minimization

- Fire flow analysis
- Vulnerability studies
- Operator training

3.2.13 PowerDEVS

PowerDEVS is a general-purpose modelling and simulation (M&S) software tool oriented towards the simulation of hybrid systems within the DEVS framework. PowerDEVS was one of the first, and nowadays one of the most advanced tools that allows the implementation and simulation of DEVS models. Its graphical user interface (GUI) provides user with graphical libraries of different blocks (e.g. sine, nonlinear function, ramp) that enable a quick modelling of basic systems. Another feature is the interconnection between PowerDEVS and the numerical package Scilab (Campbell et al., 2006). PowerDEVS simulations can make use of Scilab workspace variables and functions. In turn, Scilab can be used for further processing and analysis results from the PowerDEVS simulation (Bergero and Kofman, 2011). However, modelling complex systems with thousands of elements with use of the diagram blocks can present a challenge for a PowerDEVS modeller. Also, with no manual the further modifications to the existing blocks is inconvenient and troublesome.

Since introduction of the DEVS formalism several implementations of this theoretical concept have been developed: DEVSim++ (Kim, 1994), DEVS-Java (Zeigler and Sarjoughian, 2000), CD++ (Wainer et al., 2001), JDEVS (Filippi et al., 2002), DEVS-C++ (Cho and Cho, 1997), ADEVS (Nutaro, 1999), ModelicaDEVS (Beltrame and Cellier, 2006), PowerDEVS (Bergero and Kofman, 2011) and many others. Most of them have been designed to simulate purely discrete systems but some, e.g. PowerDEVS, integrate the QSS methods, and thereby, enabling the modelling and simulation of hybrid systems.

3.3 Conclusions

In conclusion, Simulink® provides component libraries for modeling and simulating hydraulic systems based on a time slicing approach. Can be used to develop control systems and test system-level performance. Is specifically developed to cover modeling scenarios with hydraulic actuators as part of a control system. Performs transient analysis of hydro-mechanical systems. We can parameterize our models using MATLAB® variables. Simscape® software is based on the assumption that fluid temperature remains constant during the simulated time interval. The experience and results of the design and simulation based on Simulink® are very good for the purpose of this thesis.

Moreover, this chapter introduces available simulation software tools, open source or commercial (i.e. OpenModelica, EPANET®, LabVIEW®, Dymola® etc.) which can handle complex hydraulic simulations such as large scale water distribution network systems. These are simulators for modelling and simulation (M&S) framework based upon on a *time slicing approach* i.e. numerical methods, or combination of the *DEVS formalism*. The DEVS approach brings many benefits especially to modelling and simulation of hybrids systems, such as WDSs.

CHAPTER 4. OUR RESOURCES AND MATERIALS OF TWO SOFT DRINK PRODUCTION LINE FACTORIES

This chapter focuses on the data collected from searching and studying intelligent solutions on the controlling, designing and programming of a production line. We spent a lot of time visiting and studying the factory layout of a soft drink production line and how it operates. The chapter presents an overall view of the modeling of our system model based on the research of two factories, one Greek the **ETANAP-Samaria SA (Stylos Chania, Greece)** and the **KOFOLA CeskoSlovensko AS (Krnov-Czech Republic)**.

4.1 The soft drink production line

Soft drinks can often described as sweetened nonalcoholic beverages usually based on water, which are carbonated, colored and fruit flavored (using fruit juice or pulp or other natural ingredients). So a soft drink production line is a set of sequential operations which are established in a factory where materials are mixed together through a manufacturing process to produce the end-product. The main components of this PL are written in the following list.

1. Sugar melt and mix pot
2. Syrup pump
3. Chiller (syrup chiller)
4. Frame filter
5. Water mix tank
6. Pump
7. Microporous film filter
8. Mixed liquor chiller
9. Carbonic acid water blending machine
10. filling machine and labeling machine and packaging machine

According to work [23], the soft drink manufacturing process starts with the water treatment, which is cleaned and treated the water to meet the quality-control standards and achieved high product quality and consistent taste profiles. As the ingredients are prepared, the cleaned water is piped into large, stainless-steel tanks (mixers). This is the process at which the various ingredients are added into the mixer. During this stage diet beverages are mixed with artificial sweeteners, the regular drinks are mixed with liquid sugar and if it is necessary food coloring may be added. It is common for bottling companies to acquire concentrate from other companies.

Next is the carbonation of the soft drink. Depending on the product's recipe the quantity of the CO_2 may be different (i.e. fruit-flavored soft drinks tend to have less carbonation than colas). Then the products are ready for bottling.

The bottling/filling process is taking place on a special room which is separated from the rest of the facility, protecting the products from possible contaminants. This process is highly automated increasing the productivity and efficacy. The filling room operators monitor the equipment for efficiency. Then, quality control procedures are followed where the end product is tested to ensure that the finished drink meet the quality standards.

The last stage of the production process is the packaging process. This process is highly automated as well meeting various marketplace requirements.

The Figure 4.1 presents a basic diagram of a soft drink PL.

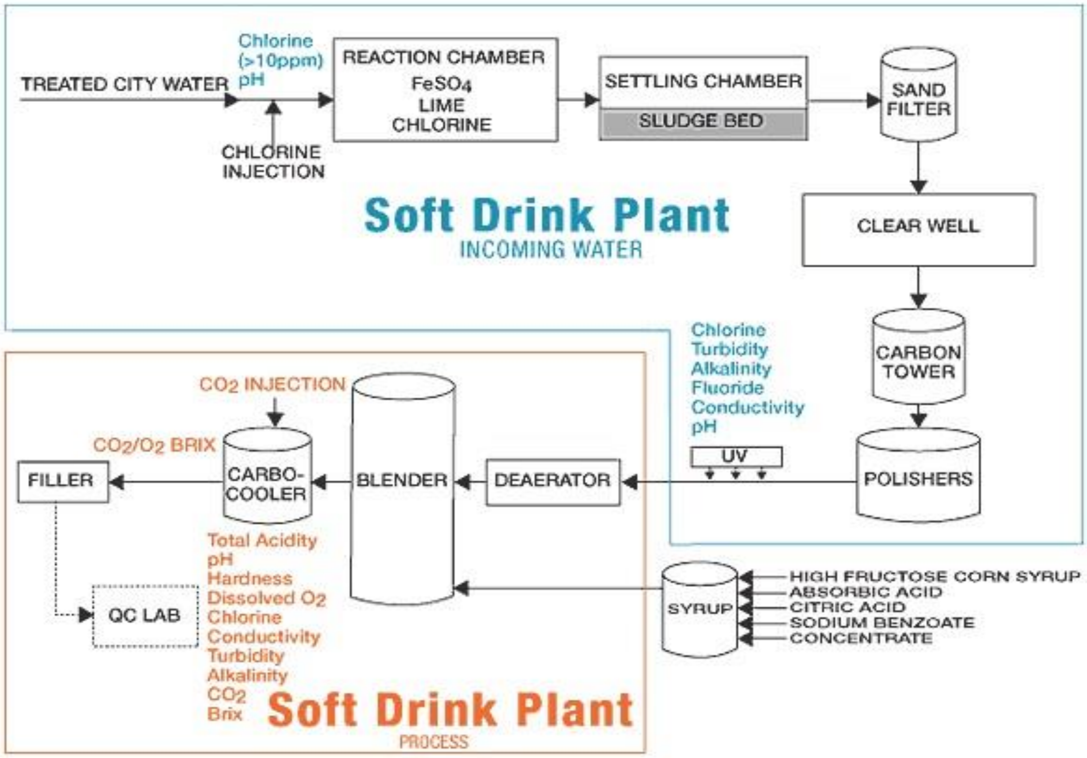


Figure 4.1 Soft drink production line

According to work [3] there are two main components of the production chain – the syrup producer and the bottler. The Figure 4.2 presents the process flow of production and distribution of a soft drink.

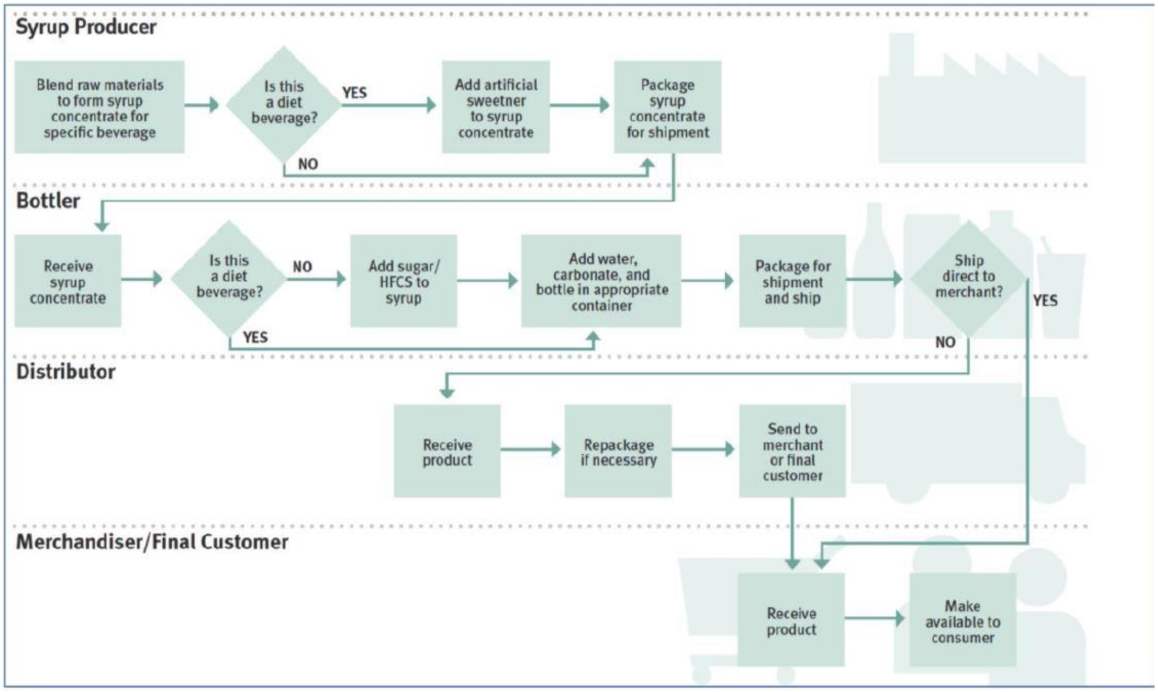


Figure 4.2 Process flow of a soft drink production line based on Pollution Research Group [3]

4.2 Data and characteristics of real soft drink production lines

An important aspect of the research is the layout and the operation of the production line because it is the key factor which are influence the production plant before start designing it. So an important feature of the production line is the tanks. During my research I had the opportunity to study the production plants of two different factories.

The research is based on my tour in two different factories. The

Table 5 presents the basic information about the two factories.

Table 5 Basic information of the production lines of the two factories

CHARACTERISTICS	ETANAP-SAMARIA SA (STYLOS CHANIA, GREECE)	KOFOLA AS (KRNOV-CZECH REPUBLIC)
LOCATION	Stylos Crete, White mountains	Moravian-Silesian Region, Krnov
AREA	8,500 sq.m.	
WATER SOURCE	Three private well in the region	Stored water on tanks
PRODUCTS	Natural table water and carbonated water (0.33 *lt*, 0.5 *lt*, 0.75 *lt*, 1 *lt*, 1.5 *lt*, 5 *lt*, 10 *lt*)	Wide range of soft drinks, fresh juice (0.33 *lt*, 1 *lt*, 1.5 *lt*, 10 *lt*)
PLANT	Bottling and packaging	Bottling and packaging
PRODUCTION LINES	4 automated production lines	7 automated production lines
PRODUCTION CAPACITY	18,000 bottles per hour (using the most advanced production line)	40-50,000 bottles per hour
BOTTLES	PET and glass bottles	PET and glass bottles, cans

The ETANAP SA factory pumped the water from the borehole “Dichalorimata” in Stylos, it is transferred through stainless steel pipes, filtered and then it is proceeding on bottling lines. The factory has 4 automated lines for bottling water. At the first line, the water is bottled in PET type bottles of 0.5 *lt*, 0.75 *lt* and 1.5 *lt* with production capacity 11,000 bottles per hour. Second line, the water bottled in glass type bottles of 1 *lt* as well as carbonated water in 0.33 *lt* with production capacity of 6,000 bottles per hour. At the third line, the water is bottled in PET type bottles of 5 *lt* and 10 *lt* with production capacity of 12,000 bottles per hour. Last but not least, the fourth line is the most advanced and it is used for PET type bottles of 0.5 *lt*, 0.75 *lt* and 1.5 *lt* with production capacity of 18,000 bottles per hour.

On the other hand, KOFOLA CeskoSlovensko AS factory has to use many different water tanks and the reason for this is that the factory manufactures a wide range of soft drinks and water bottling that requires different water quality based on the product’s recipe. So storing water is an important aspect of the production process. Moreover, during my research on the Czech factory I noticed that the mixers are on the second level of the facility and near the chemical laboratory so that the chemists could analyze the quality level of the water and syrup.

Secondly, another area that needs attention is the required pump stations. Both factories had a complex system of pumps and valves that was difficult to analyze. The task of my research was to design a simplify version of such systems. During my tour at ETANAP-Samaria SA factory I had the change to discuss about the production with the president and chief-engineer Mr. Apostolakis, whose guidance and suggestions on the procedures and operations based on his factory, was implemented to the system design.

According to the works [1]-[2]-[3] and the research on this two different facilities, the basic design of the system is created which is presented in the next sub-chapter.

4.3 Basic elements and approach of the system model of a soft drink PL

This subchapter discusses the designing choices, features and overall the basic elements of the PL system's design in general. So the system's design focuses on three main categories which includes all the main components. The first category includes information about the tanks of the system. The second includes the control system. And last but not least, the third category includes the intelligent mechatronic components.

4.3.1 Tanks: How tanks affects the design of the production line

Previous subchapter presented the data that was gathered during the research and included information about the tanks of the system. Tanks are an important factor for the production line because they used to store and protect the products during filling and manufacturing process in order to avoid contamination. As presented, the topology and size of the tanks vary based on the production plant, needs and infrastructure.

The key feature of the tanks is the size which is connected with the recipe and topology of the product. Another key feature is the number of the tanks that the production plant need to operate fluently and efficiently. For instance, the Czech factory was using several tanks with different water type and quality. So different products needs different quantities of the same or different raw materials. With that said, according to my research and Mr. Apostolakis guidance we designed our system having 1 by 5 aspect ratio which means for every 1 m^3 of syrup we use 5 m^3 of water. Another aspect that need attention is the factory production plant. According to the research, the production plant needs to conserve a 6 m^3 of product per hour so that can manage the production of 12* 10^3 500 *ml* bottles or a 4$*$ 10^3 1.5 *lt* bottles. The system's tanks meets both the production needs and standards.

4.3.2 Designing an intelligent Control System for a PL

Nowadays the technology of the machinery is based on individual control units which are especially developed for the machine and its operation (supervisory or direct control division see Figure 2.1). For example, the filling machine is an automatic machine which is manufactured to process different types of products (different type of soft drink) and bottles, different capacities means different bottles or different type such as PET or glass. Even though, the machine is connected to a higher level network which is monitoring and controlling all the production process and machinery, managing the operation is done by a sensor network controlled by machine's control unit (the direct control division). The sensors are taking real-time measurements and control system processes the data on the fly.

So it's really necessary for the research to develop a control system that meets the modern standards and controls the system based on the specifications. The control unit is a distributed control system that consists of three control sub-systems each one manages a different part of the production line, we divide the production into three different pipelines. Every sub-system consists of two different level control units. So in total there are six control units responsible for the pipelines and one more for the state of the PL. Having seven different control units we manage to reduce the complexity of the control system and have the ability to repair and reprogram each sub-system independently. Moreover, having a multi-agent control system without a centralized control unit creates a network of sensors and control units (agents) which a communication can be done among them.

The control system uses the sensors output as inputs and calculates the models phases. In Figure 4.3 it is illustrated the phases of the system.

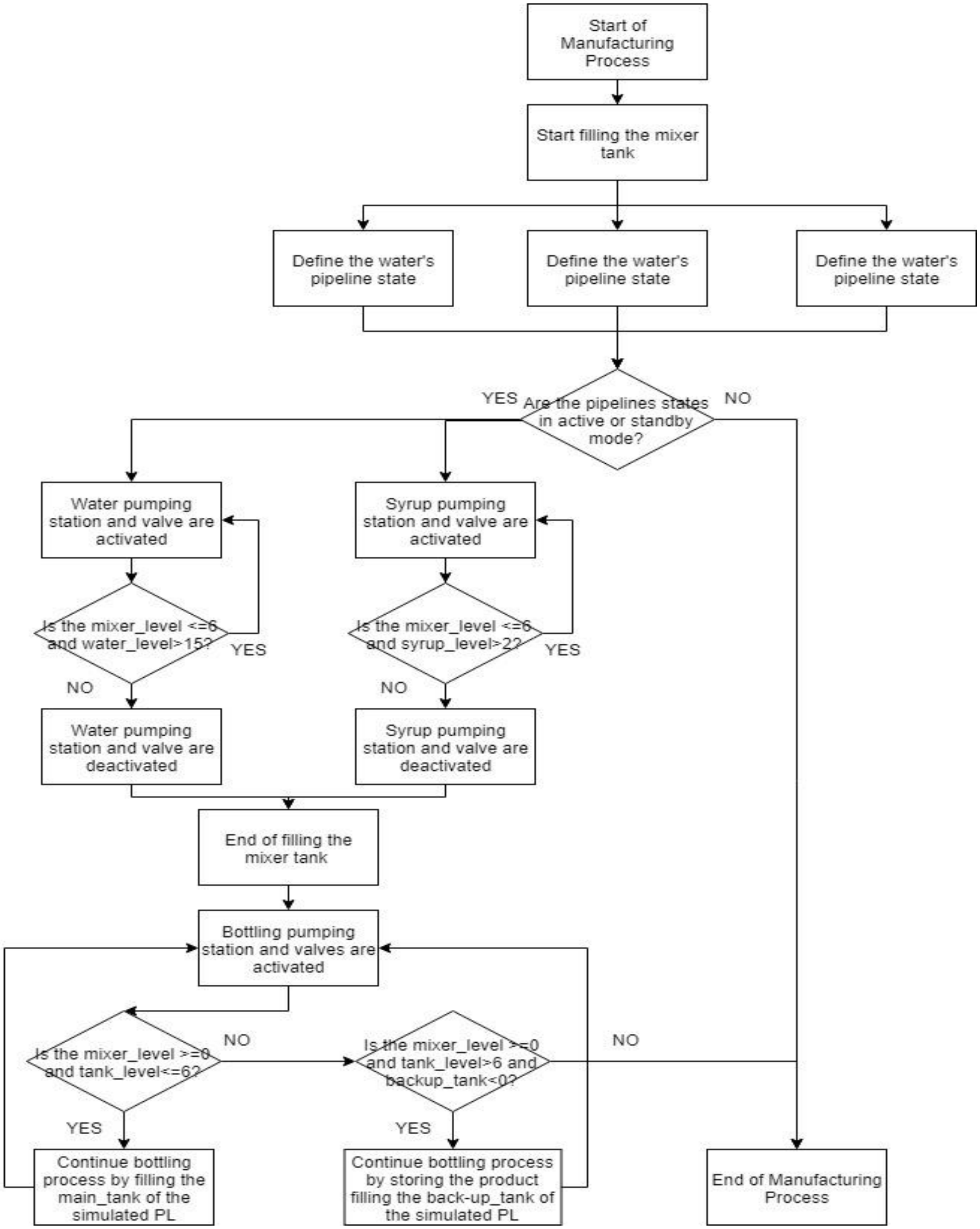


Figure 4.3 Process diagram of a soft drink production line

Based on the subchapter 4.1 (paragraph 2) and Figure 4.1, the water tank as well as the syrup tank are a more complex systems. The incoming water has to be treated and cleaned before use in order to meet the quality-control standards and the syrup must be manufactured before the production of the soft drink begins. As a consequence, for the sake of simplicity we decide not to include to our simulation PL the water treatment and the syrup preparation to preserve the model as simply as possible.

4.3.3 The use of intelligent Components in a PL

The future of production systems are intelligent components. In order to characterize a component "intelligent" it must contain some kind of CPU processor for decision making and storage for information storage. This term refers to self-contained, autonomously functioning mechatronic assemblies. They optimise the production process thanks to their increased functionality – from the set-up stage through to ongoing operations. Such components are control valves, pumps and sensors. Since the production of many customized products rather of a single product is necessary, the industries forces on investing on more modular and reconfigurable production machinery.

Such components are equipped with embedded control units and can be implemented into machines and systems. The use of such intelligent components will result reconfiguration of the production system and essential design benefits.

4.3.4 Basic design approach of a PL

Based on the data which are analysed earlier in this chapter, the design of such a production line depends on the production plant and the products themselves as well as the infrastructure of the factory as is presented earlier with the two different factories. In our research studies we use a simplified approach of such a real production line.

So based on that, the production line consists of two initial fluid tanks which one is full of cleaned and treated water and the other one with syrup (see Figure 5.5). The manufacturing process takes place in a mixer tank which in our design is represented as a tank with 6 m^3 volume of fluid.

Then, there is the bottling process where bottling machines used to fill the bottles with product. In our research the last process/phase is represented with 2 tanks (main and back-up), the first one represents the main production line where the bottling process takes place and the second represents a back-up tank mainly for storage purposes.

Naturally, the system starts by pumping water and syrup into the mixer. Obviously, water and syrup tanks are connected with the mixer in order for the manufacturing process to start and both are connected with one another with resistive pipes. Alongside the pipeline there are three sensor clusters monitoring the subsystem’s pressure and flow and a pumping station regulating the flow of fluids. Then the mixer is connected with a resistive pipeline with the bottling machines. Importantly, sensor clusters are monitoring the pipelines pressure and fluid flow and a pumping station is responsible for the flow regulation as well.

4.4 Conclusions

According to our research of two soft drink factories production lines, one Czech and one Greek, there are many different approaches regarding the design and operation of a production line, it seems reasonable to assume that the fundamental design of a modern soft drink production line has the same structure in every case. With this in mind, in the following chapter we model and simulate our simplified PL plant.

CHAPTER 5. MODELING AND SIMULATION OF A VIRTUAL SOFT DRINK PRODUCTION LINE (PL)

An overall view of the layout and operation of a soft drink production line is given in the CHAPTER 4. Having that in mind, we model and simulate our virtual plant like an action one modern production line. This chapter is going to describe the proposed model which is based on the findings of previous chapter.

Our virtual model focuses on the behavior of the pump station and how the variation of the pumps speed will affect the system's flow (VFD). The pumps speed regulation is controlled by the synchronism of a DCS system consisting of seven separate control units which will be analyzed in the next chapter. In order to understand the system's controller operation, it is crucial first to understand the assembly of the system and its main modules.

To that end, subchapter 5.1 introduces the necessity of the virtual construction of the PL. The subchapter 5.2 presents the virtual construction of the production line simulated in Simulink®. The subchapter 5.3 defines the system's blocks. At the end a conclusion is made, based on the whole chapter.

5.1 Necessity of the virtual construction of a production line (PL)

According to work of Sidel Group [24], investing in new equipment has been proved that it is a big decision for any manufacturer. With the use of simulation software tools (see CHAPTER 3), the brand owners and engineers can simulate and test the line before they decide on the right set-up for their needs. Furthermore, the simulation software tools enable them to keep their operating costs to a minimum.

The virtual construction of a production line allows the engineers to check all details before exporting the virtual model into a simulation tool to see how it behaves, many scenarios can be checked and monitored. For example, virtual construction allows a simulated model to perform a large part of the debugging processes ahead of installation. So this type of technology is expected to change the way manufacturers install and upgrade their equipment.

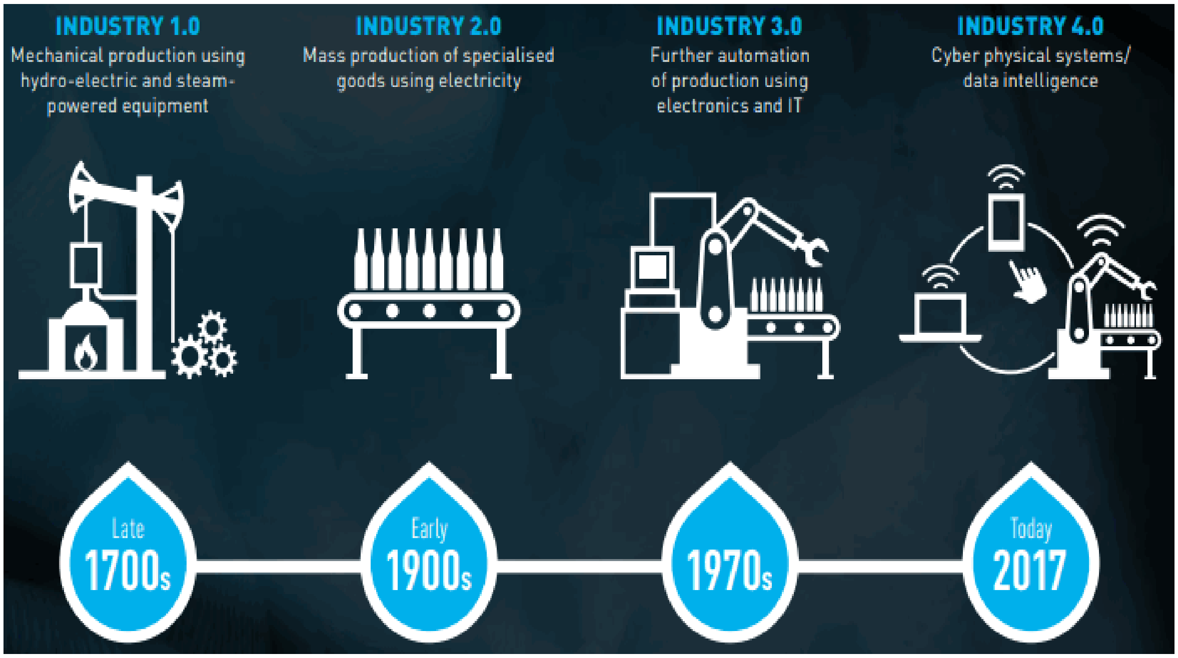


Figure 5.1 The four phases of industrial revolution found on Inline by Sidel Group

5.2 Virtual model of the pump station for a soft drink PL in Simulink®

The model is divided into many parts and the reason for this is to facilitate implementation and problem solving during construction. Provided that, the design of the model is simple and functional yet easy to control and it's customizable according to the research needs. The simulated productions line consists of various components found on the Simscape fluids™.

In Figure 5.2 we are presenting the model's incorporated blocks.

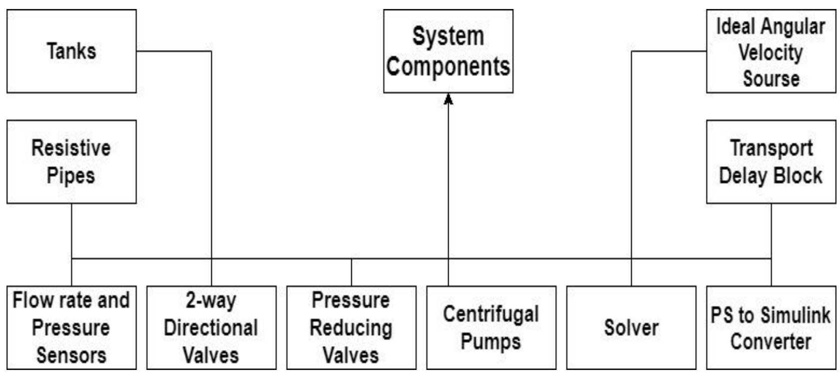


Figure 5.2 Block diagram of the simulated PL components

The Figure 5.3 and Figure 5.4 present the part a and part b of the block diagram of the simulated production line which contains five liquid tanks, twenty sensor clusters, three pumping stations and six valves.

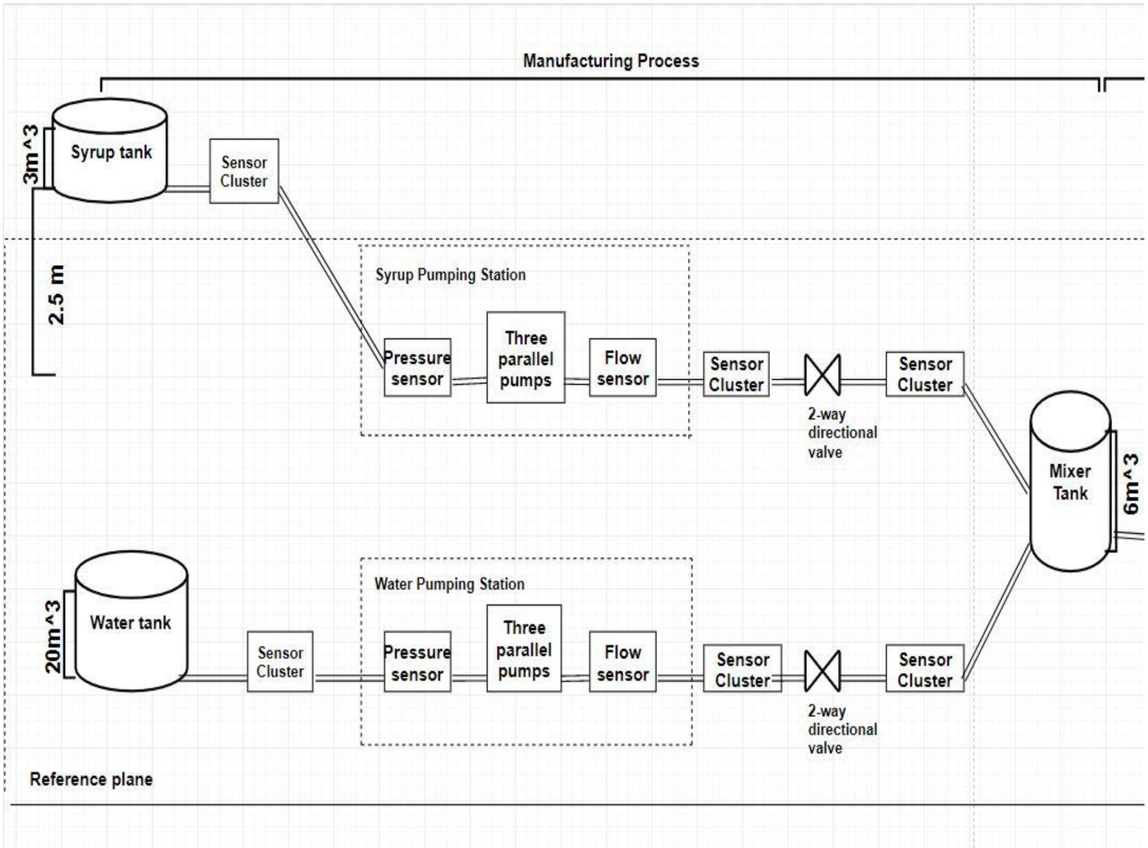


Figure 5.3 Block diagram of the manufacturing process of simulated PL (part a). The PL (part a and b) contain five liquid tanks, twenty sensor clusters, three pumping stations and six valves.

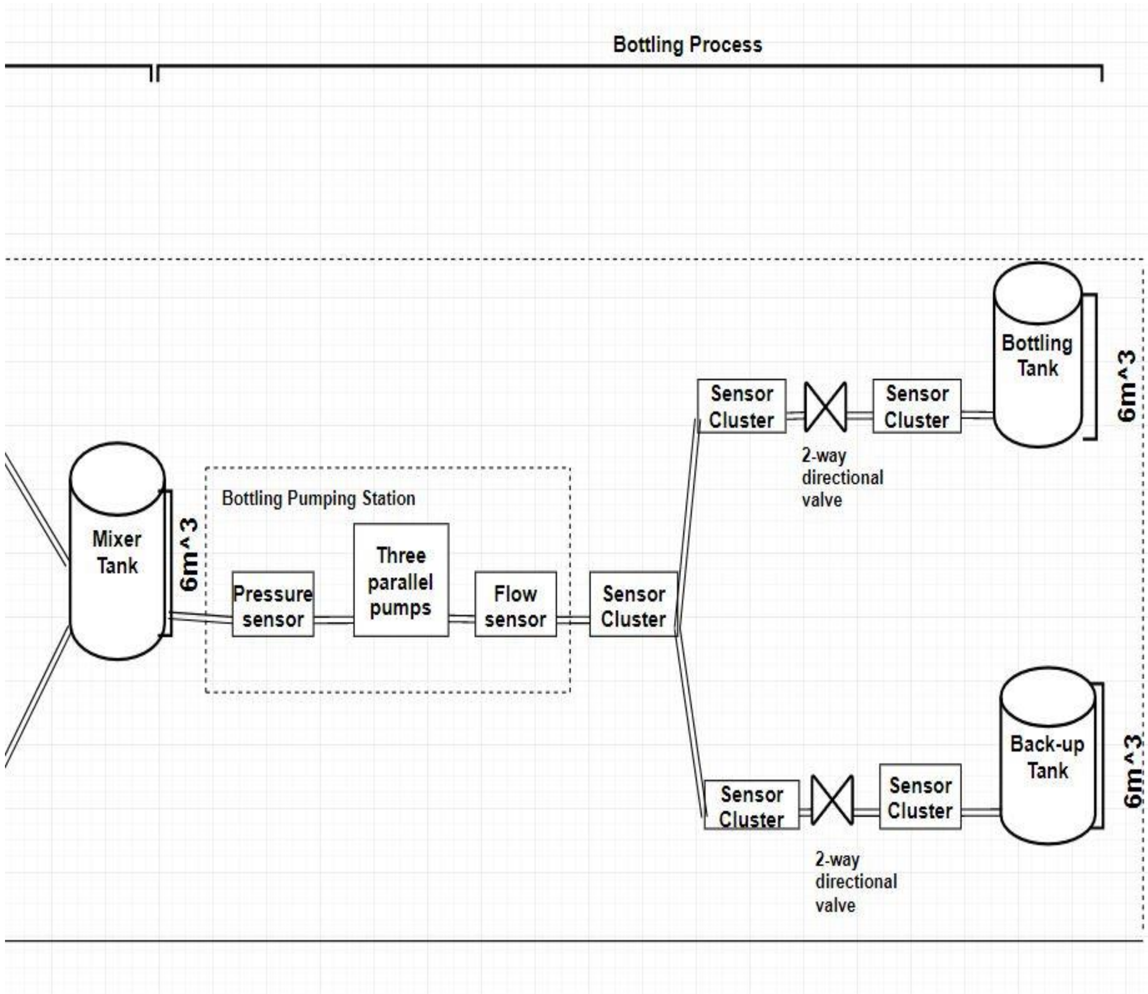


Figure 5.4 Block diagram of the bottling process of the simulated PL (part b). The PL (part a and b) contain five liquid tanks, twenty sensor clusters, three pumping stations and six valves.

The simulated production line consists of five liquid tanks and each tank is connected to a separate pumping station and a series of pressure rate and flow rate sensors. The next tables provide an overview description of the tanks, valves, pumps and sensor cluster which are used in the model.

Table 6 Tanks parameters and description of the simulated PL

NAME	TOTAL VOLUME (m^3)	ELEVATION (m)	DESCRIPTION
WATER	20 m^3	0 m	Contains the treated water
SYRUP	3 m^3	2.5 m	Contains the end-product of syrup
MIXER	6 m^3	0 m	Contains the 1 m^3 of syrup and 5 m^3 of water
BOTTLING	6 m^3	0 m	Contains the liquid soft drink and represents the bottles
STORAGE (BACK-UP)	6 m^3	0 m	Protects any quantity of liquid soft drink hasn't bottled

Table 7 Valve types in simulated PL

VALVE TYPE	QUANTITY
2 WAY DIRECTIONAL VALVE	4
PRESSURE REDUCING VALVE	2
TOTAL	**6**

Table 8 Pump type of the simulated PL's pumping station

PUMP TYPE	QUANTITY PER STATION (POSITION)	PUMP DESIGN DELIVERY	REFERENCE ANGULAR VELOCITY
CENTRIFUGAL	3 (parallel)	130 *lpm*	1770 *rpm*
TOTAL	**9**		

Table 9 Sensor types in simulated PL

SENSOR TYPE	QUANTITY	WATER PIPELINE	SYRUP PIPELINE	BOTTLING PIPELINE	PUMPING STATIONS
FLOW RATE	20	3	3	5	9
PRESSURE RATE	20	3	3	5	9
TOTAL	**40**	*6*	*6*	*10*	*18*

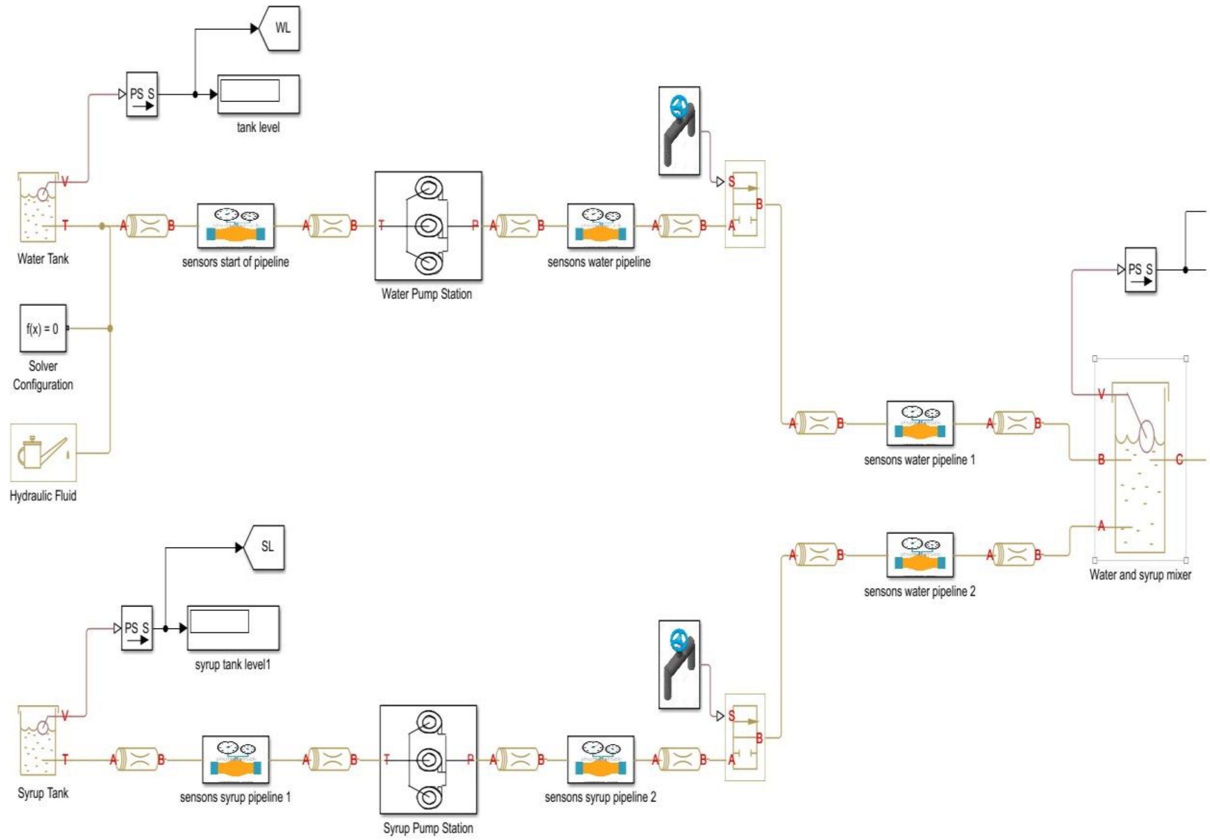


Figure 5.5 Simulink® simulation of the manufacturing process modules of a soft drink PL (part a of PL, see Fig.5.3)

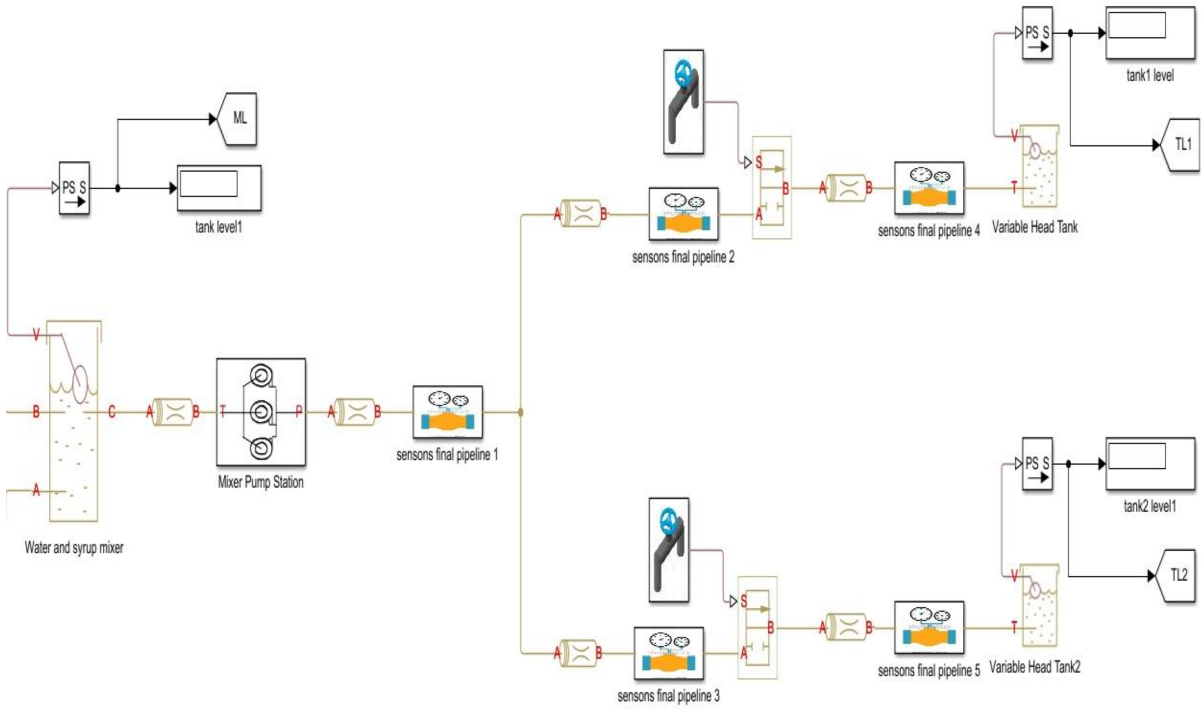


Figure 5.6 Simulink® simulation of the bottling process modules of a soft drink PL (part b of PL, see Fig. 5.4).

In Figure 5.5 and Figure 5.6 it is shown the system's configuration with all its modules as implemented in Simulink®. As it illustrated in these figures, each tank is connected with another one using a number of pipes, creating the pipeline. As presented in Table 7, the valves of the model are 2-way directional valves as well as pressure reducing valves. The 2-way directional valves let the liquid flow depending on system state.

The sensors cluster block consists of the sensors which were presented in Table 9. These blocks consist of pressure rate and flow rate sensor monitoring the pipeline.

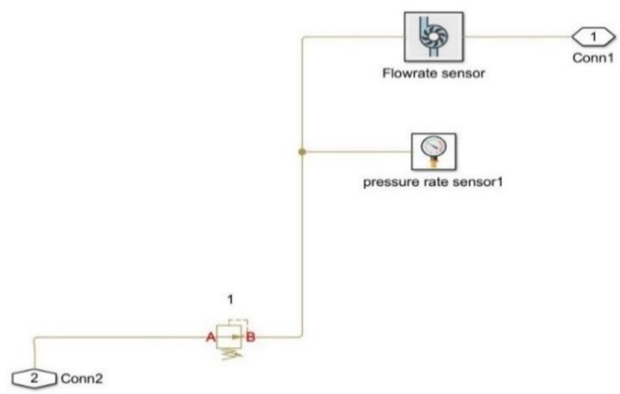


Figure 5.7 Simulink® simulation of Sensor Cluster

As it is shown in Figure 5.7 the sensors cluster structure. Yet there is another block, a pressure reducing valve that is used to maintain reduced pressure in a portion of the system. Accordingly, this block is used only in the first cluster of water and syrup tank respectively because of the steep increase in pressure.

Last but not least, there are the pumping stations of the system. Table 8 presented an overview of the pump which the model's pumping station has to achieve a steady flow of liquid. The Figure 5.8 presents the Simulink design of the system's pumping station. Every station consists of three centrifugal pumps parallel connected to each other.

Moreover, there are sets of pressure rate and flow rate sensors for every pump, so that the operation of every individual pump can be monitored. The pumping stations are controlled by Variable Frequency Drives (VFD) which are described in the next chapter.

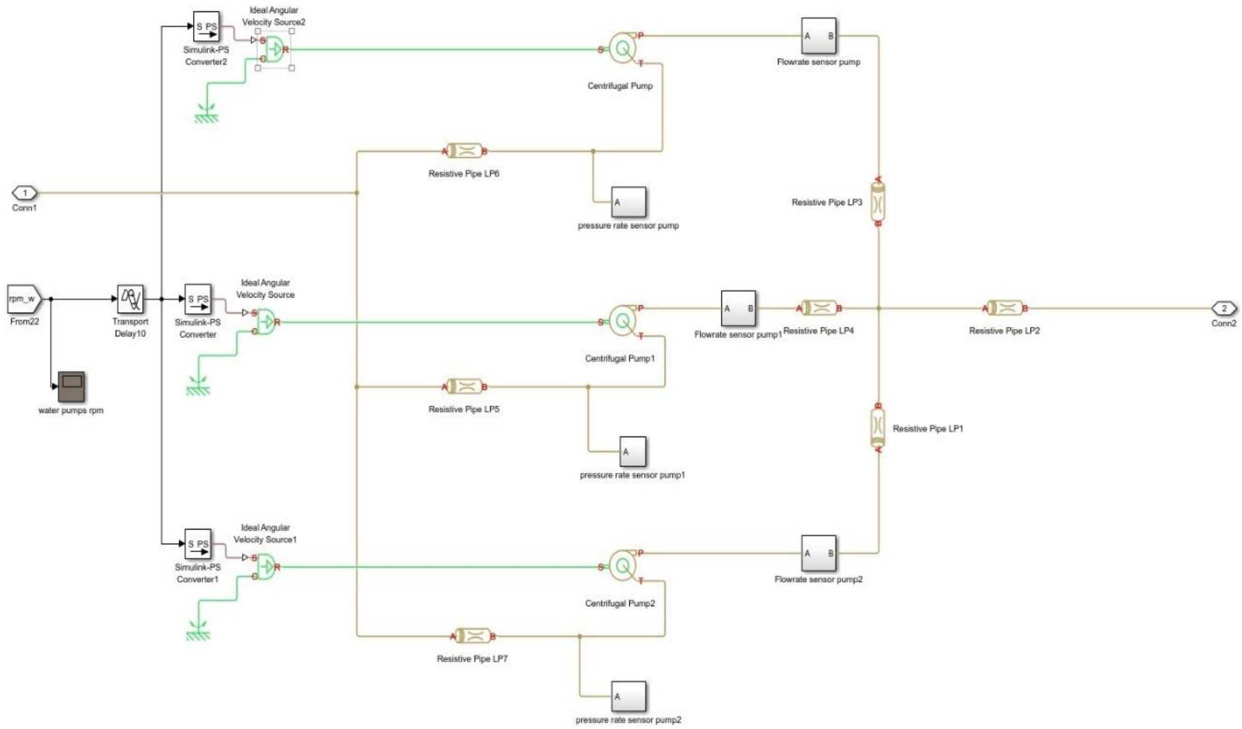


Figure 5.8 Simulink® simulation of the PL pumping station

5.3 Declaration of the simulated system's blocks

As it is shown in Figure 5.3, Figure 5.5, Figure 5.6 and Figure 5.8, the design and some details of the model and pumping station. This subchapter will focus on the individual blocks of the system.

This model is designed in Simulink®, a plugin tool of MATLAB® using the Simscape Fluids™ library which was presented in CHAPTER 3. This Simscape Fluids™ library has the capabilities for simulating many type of system like hydraulics, providing different types of blocks such as pumps, tanks, pipes etc. as presented in Figure 3.2.

However, it is critical first to discuss about the blocks chosen for this model and then present the options and blocks lists.

To begin with, the tanks, pumps and the sensors cluster have been defined on the previous subchapter, so continue with the resistive pipe blocks which simulate a basic hydraulic pipeline which accounts for friction losses and port elevations.

Next, the control valves block which are pressure reducing valves and two way directional valves. In Figure 5.9 and Figure 5.10 the valve and valve signal blocks are presented. The valve is a two-way directional valve that controls the liquids flow. If the signal port is positive the valve is open otherwise it's closed. The valve signal block opens and closes the valve according to valve controller and system state. Initially, the valves are closed.

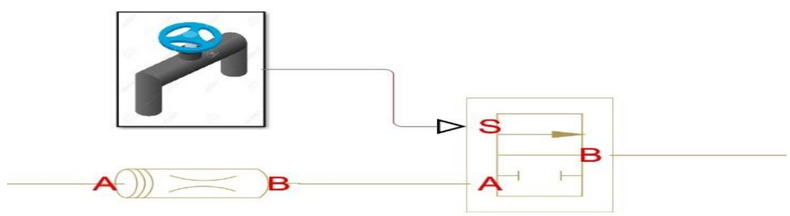


Figure 5.9 Simulink® simulation of two way directional valve

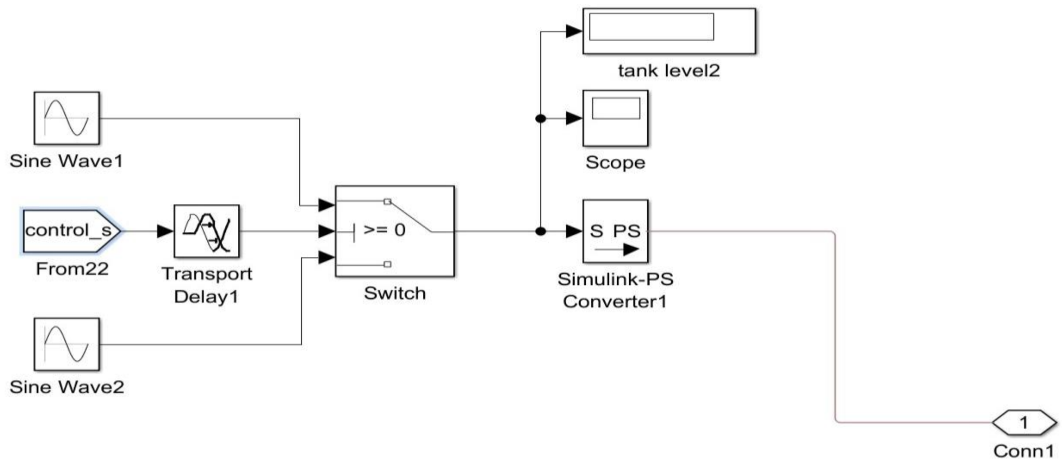


Figure 5.10 Simulink® simulation of control valve signal control

To simulate a dynamic system a solver is needed which computes its states at successive time steps over a specified time span, using information by the model. During the simulation of the model all the available solvers were tested, both fixed and variable step size, and the selected solver is the ODE 14x.

5.4 Conclusions

In conclusion, in this chapter we focus on the necessity of the virtual design of the model. The virtual model of a soft drink production line is implemented in Simulink of MATLAB®, using the Simscape Fluids™ (formerly SimHydraulics®) library. Also, we described all the blocks (like tanks, pumps, valves and sensor clusters) of the virtual simulated PL of a soft drink factory are presented and explained.

CHAPTER 6. MODELING AND SIMULATION OF A DCS CONTROL SYSTEM FOR SOFT DRINK PRODUCTION LINE

The previous chapters analyze all the components of the designing model and present the final design of a basic soft drink production line. Having a large number of intelligent mechatronic components like control valves, pumps and motors it is necessary to design and create a control system which will manage the system efficiently and potentially minimizing time and energy cost. Even though, the research's goal is not the energy costs, the use of a distributed control system to operate and manage the system can achieve reductions in energy costs and minimize production time. To put it another way, the controllers are designed to operate the system so that it can effectively manage the system configuring the field devices on the fly and when is really needed to terminate the operation of the PL for safety reasons.

Having that said, this chapter will focus on system analysis of the control units developed during the research. So the subchapter 6.1 will present the methods from which our control system is designed. Next, the subchapter 6.2 will focus on the design and implementation of our control system. Lastly, the subchapter 6.2.1 will conclude based on research presented in this chapter.

6.1 Distributed Intelligence: Proposed Control method for a soft drink PL based on DCS and MAS approaches

In the resent years, the production plants became more complicated and costly. This is due to the complexity of the products as well as the manufacturing process. In order to increase flexibility of the production systems, intelligent mechatronic components are used. Such components can be more reconfigurable than the traditional components due to embedded controls.

A distributed control system is a computerized control system for a production plant or process, which independent controllers are spread throughout the system. As the work [2] suggested the basic idea of DCS is that each physical element-part of the system like a pump or valve is directly connected with its own control unit, replacing the central control unit. As a result, DCS increases the flexibility of the maintenance, design and correcting the system's behavior. In other words, the operator can locate and solve system's errors and problems easier, supervising each part of the system separately.

In order to improve the robustness of such systems the most common approach and useful tool is multi-agent systems (MAS). In works [13]-[14], MAS is a computerized system composed from intelligent agents in which every single agent is connected with another one in order to achieve its tasks.

In conclusion, the authors of [20]-[21] suggested the combination of decentralized logic, distributed deployment and intelligent control results in a new approach often referred to as "Distributed intelligence". Considering all the above, our system's control units makes use of the DI approach which will be analyzed in the next subchapter.

6.2 Design and simulation of Distributed Control for a soft drink PL

The previous subchapter is an introduction on the control approaches which are used designing the system's control unit. The basic idea is to use several separate control unit's connected each other making a distributed system. The subchapter will present the virtual design and simulation of our control system.

In order to design a distributed control system, DCS:

- The production line is divided into three pipelines (1^{st} water, 2^{nd} syrup and 3^{nd} bottling).
- Each pipeline is monitored by two control units: a) one manages individual components (FD level) and b) the other controls the state of the pipeline (direct control or plant supervisory level).
- Lastly, there is a control unit which is monitoring the states of all pipeline is the responsible for the communication of the control units (direct control level).

The following table presents the control units of the simulated system's pipelines.

Table 10 Control units of the simulated system's three pipelines

PIPELINE	FIELD DEVICES CONTROL UNIT	PIPELINE STATE CONTROL UNIT (PLANT SUPERVISORY LEVEL)
1ST WATER	Monitoring and control the pumping station and valve	Monitoring the water pipeline flow rate Update the state of the pipeline
2ND SYRUP	Monitoring and control the pumping station and valve	Monitoring the syrup pipeline flow rate Update the state of the pipeline
3ND BOTTLING	Monitoring and control the pumping station and valve main (bottling and back-up line)	Monitoring the bottling pipeline flowrate Update the state of the pipeline

According to Table 10 for every pipeline correspond two control units, a FD control and a state control unit. The simulated PL consists of 3 pipelines so six control units as well as a seventh for the PL state control. The implementation of the controllers is a MATLAB®-based function which is using signal outputs from the system as inputs to decide how the individual devices should react when the liquids flow changes. This decision is made based on the system current condition like the water, syrup and mixer tank level or flow respectively.

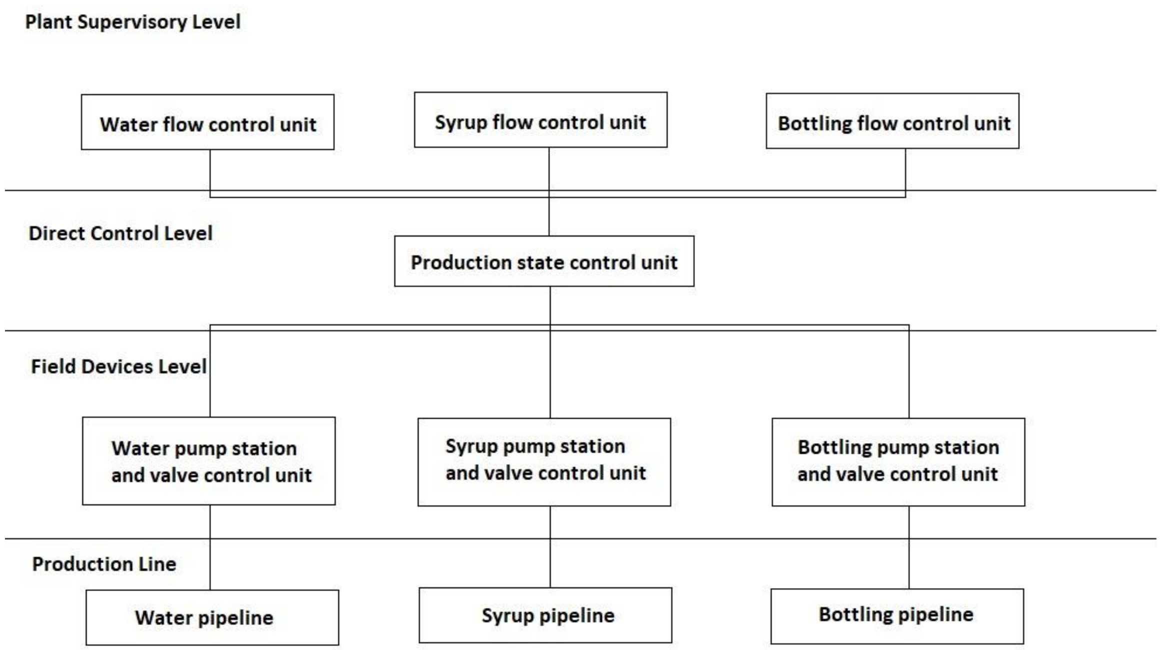


Figure 6.1 The control levels of our proposed DCS for the simulated soft drink production line

The Figure 6.1 presents the custom design DCS, each control unit and the functional level they belong. Each one of these control units is designed based on the research's result which are analyzed in 0 and they are presenting in the following subchapters.

6.2.1 Water pipeline Distributed Control Units of the simulated PL

As it is shown in Figure 6.2 there are two control units for the water pipeline operation. The first control unit is responsible for monitoring the water flow through the pipeline (state of the pipeline) and the other one is responsible for monitoring and controlling the field devices of the water pipeline such as pumping station and control valve.

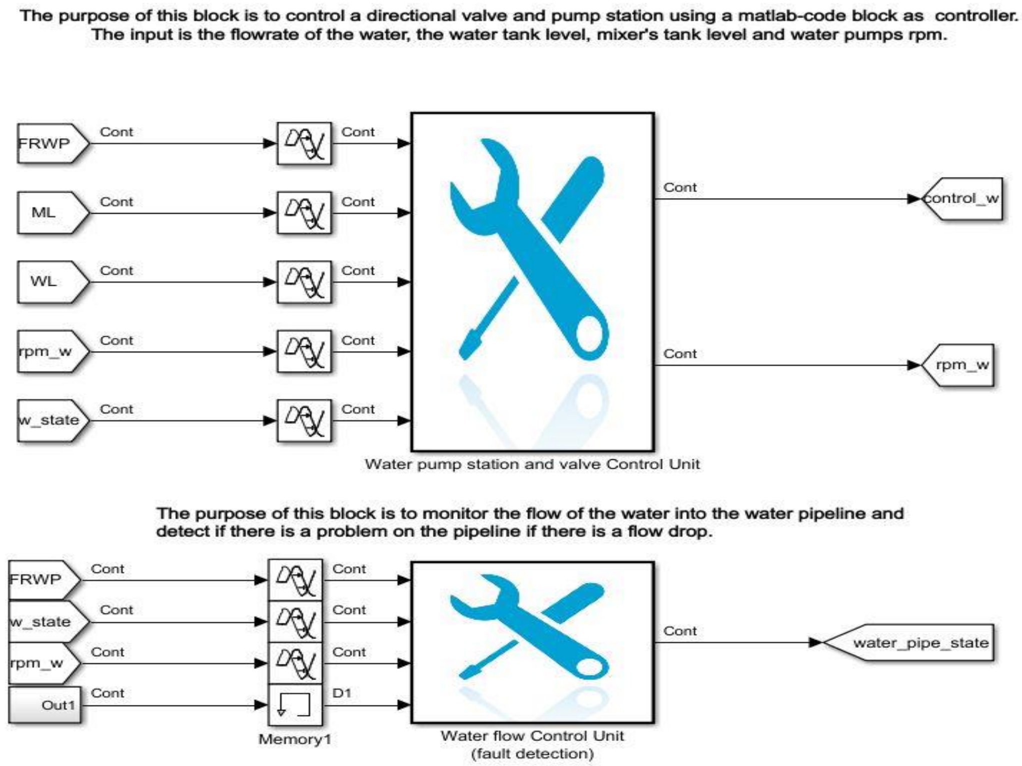


Figure 6.2 Simulation in Simulink®. Water pipeline Control units of the simulated PL

The figure 6.2 presents the block diagram of the water flow control unit. The controller's inputs are the current water flow rate, the state of the pipeline and current and previous *rpm* values. This unit is a simple controller which is monitoring the flow of the pipeline and based on that manages to detect faults in the pipeline such as pump or valve malfunction. The inputs of the control unit is the flow rate of the pipeline as well as a feedback signal which is the previous state of the pipeline. The pipeline's states are operational, stand-by and error.

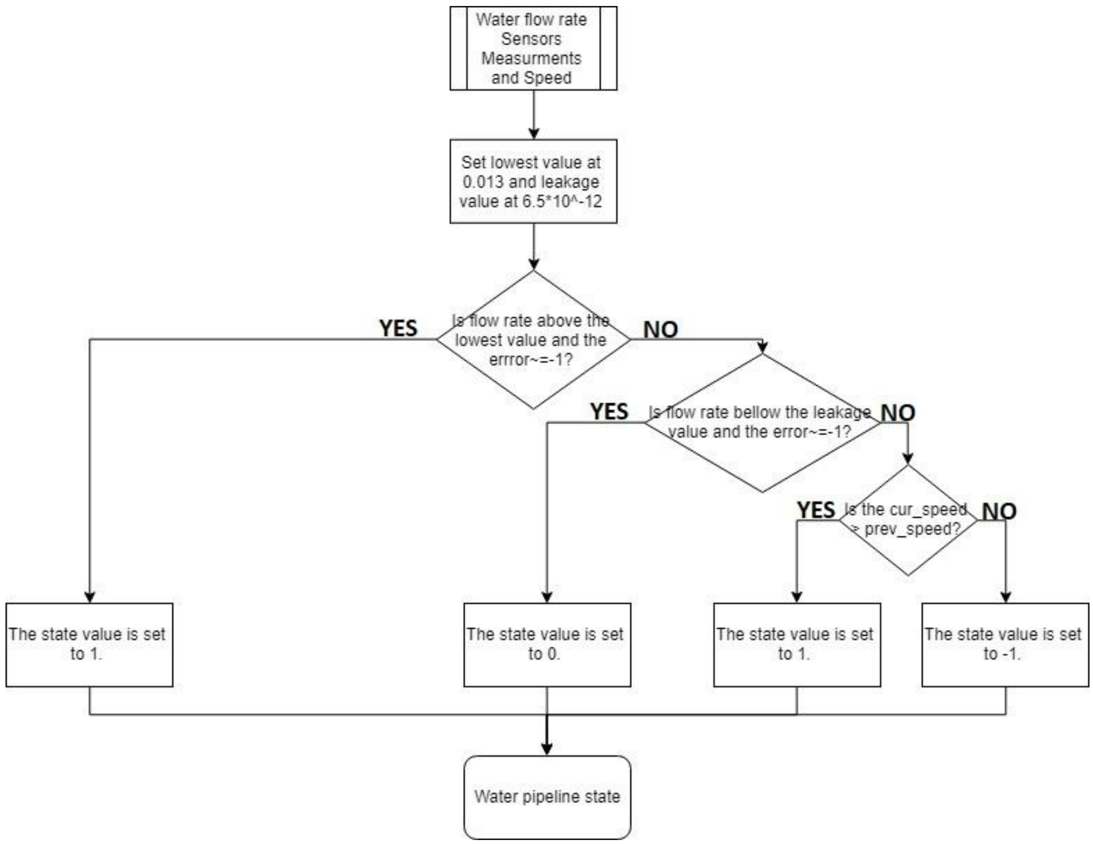


Figure 6.3 Boolean Control Algorithm for the water flow control unit

The second control unit manages the operation of the water pump station and directional control valve, so it's responsible for the water supply to the mixer. In Figure 6.4 it is shown the block diagram of the water tank control unit.

The controller's input are the current flow rate, the current mixer's and water tanks level and the *rpm* of the pump station. The outputs are the control signal which is a signal that manages the water valve operation, the signal that is used to link the water tank controller to the final tanks controller and lastly the *rpm* signal that is used to change the *rpm* of the water pumps.

The controller starts by checking the current condition of water and mixer tank. If the system is on manufacturing process where the two tanks are on the appropriate limits, right quantities of water and syrup, then decides whether to increase or decrease the *rpm* based on the current flow on the system. If not, the controller shuts down the water supply by closing the water's tank directional valve and rump station. In practice, using Simulink® the controller couldn't drop the *rpm* to 0 *rpm*, instead the pump station is operating with 1 *rpm*. Based on the recipe the water tank has to supply with 5,000 *lt* or 5 m^3 of clean water and the mixer's tank capacity is 6,000 *lt*. So controller needs to achieve the average flow of **0.001388** m^3/s.

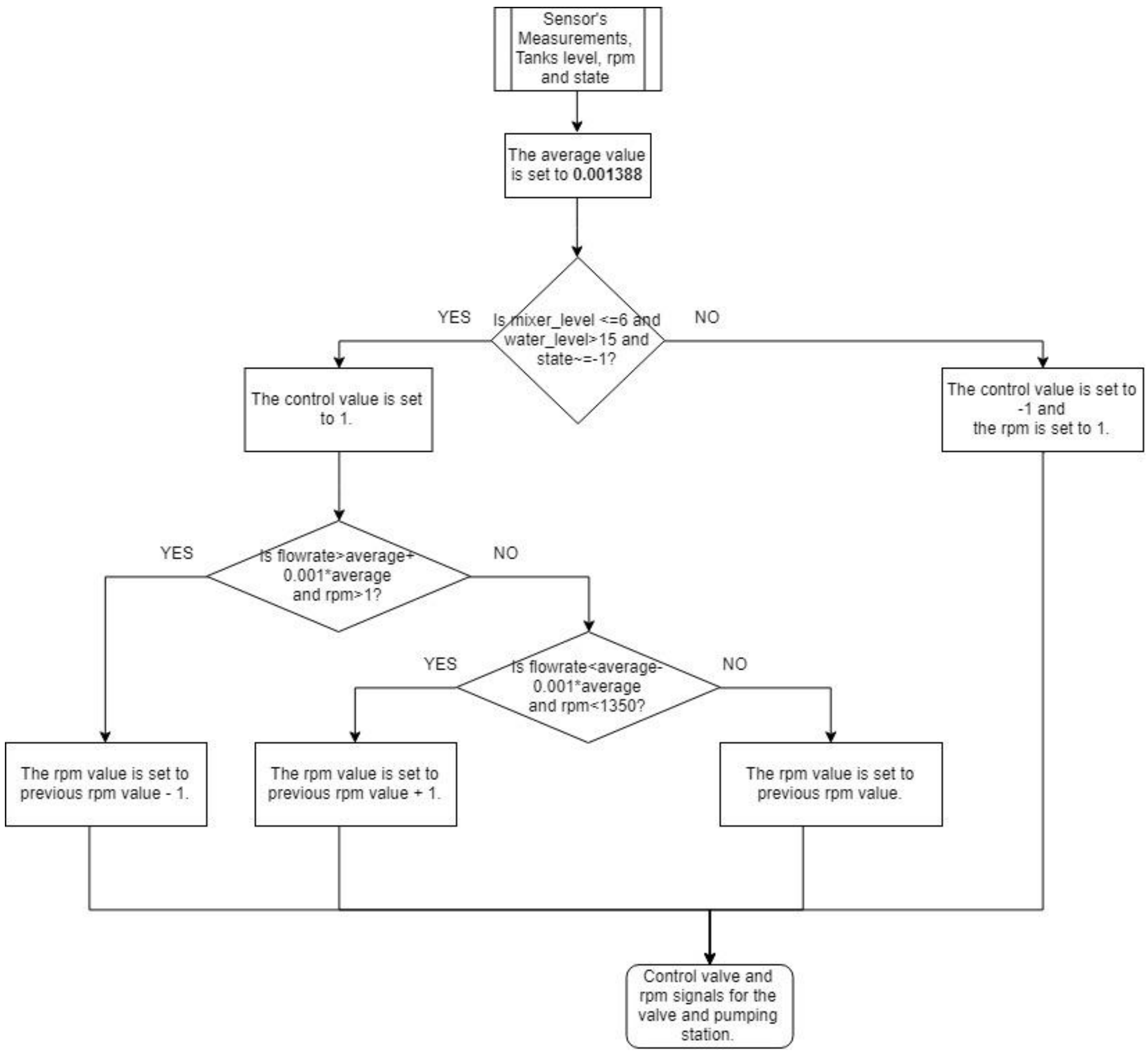


Figure 6.4 Boolean Control Algorithm for the water pump station and valve control unit

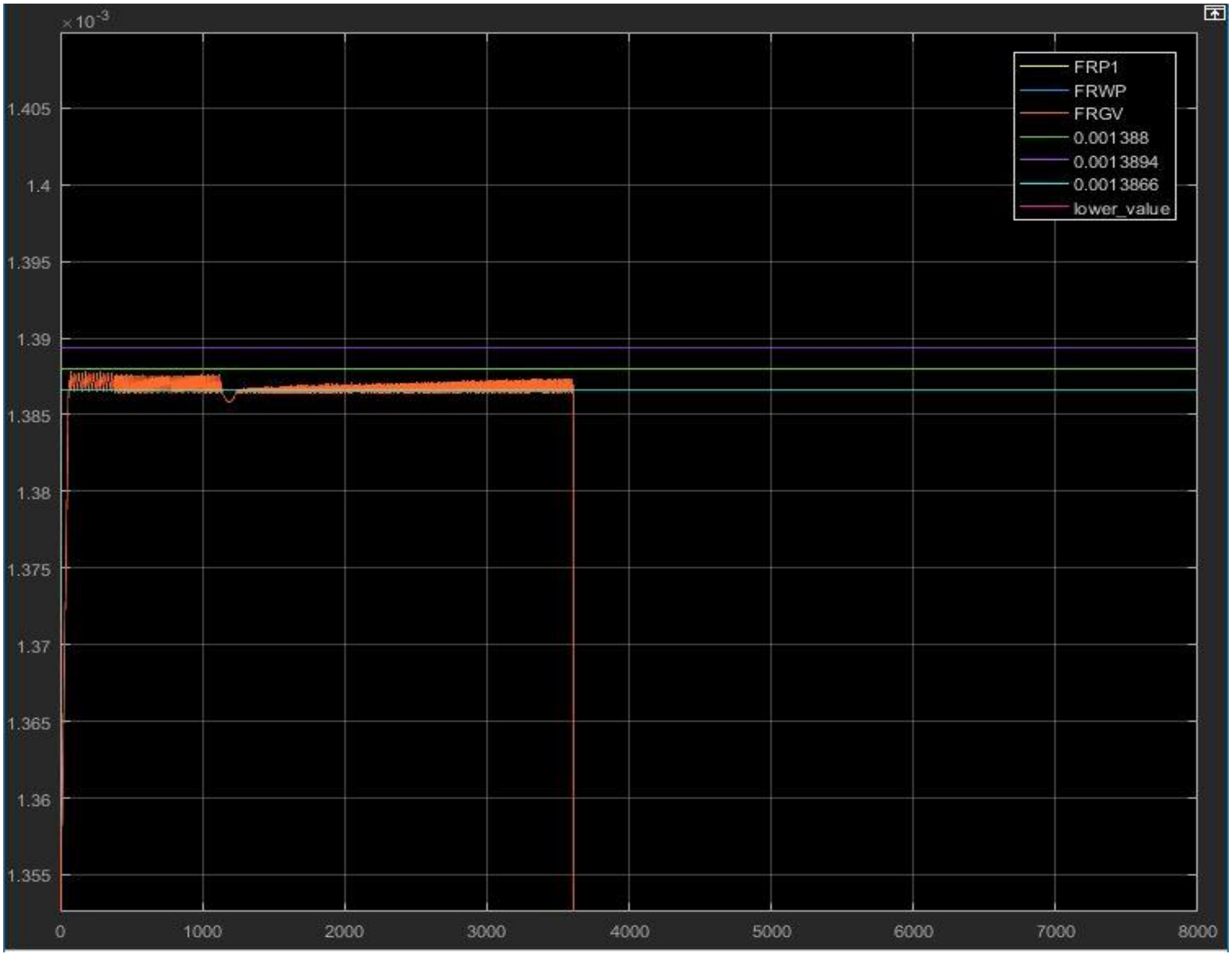


Figure 6.5 Simulation result. Flow rate diagram (m^3/s) vs time of water supply system. The time axis is valued in sec (0 to 8000) and the flow rate axis is m^3/s (1.35 to 1.41*10^{-3}). Orange: of the system, purple: the upper value, green: the average value, cyan: lower value, red: lowest operational value

The Figure 6.5 presents the flow rate diagram vs time of the water supply system. The time axis is valued in seconds and the flow rate axis is m^3/s. The target of the control unit is to maintain the flow between the upper and lower value so that that mixer tank receives 5 m^3 of water in 1 hour. The current flow rate starts really low and stabilized the flow rate at the operating range (between the upper and lower values) until the manufacturing process is over and the water supply operation is suspended.

The Table 11 presents the diagram's colors providing a description as well as the values of each one.

Table 11 Colors description of the water flow diagram

DIAGRAM'S COLOR	DESCRIPTION	VALUE
ORANGE	The current flow rate	Current value
PURPLE	Upper value	**1.3894*** $\mathbf{10^{-3}}$ m^3/s
GREEN	Average value	**1.388*** $\mathbf{10^{-3}}$ m^3/s
CYAN	Lower value	**1.3866*** $\mathbf{10^{-3}}$ m^3/s
RED	Lowest value	**1.3*** $\mathbf{10^{-3}}$ m^3/s

6.2.2 *Syrup pipeline Distributed Control Units of the simulated PL*

The implementation of the syrup pipeline control unit is similar with water's control unit.

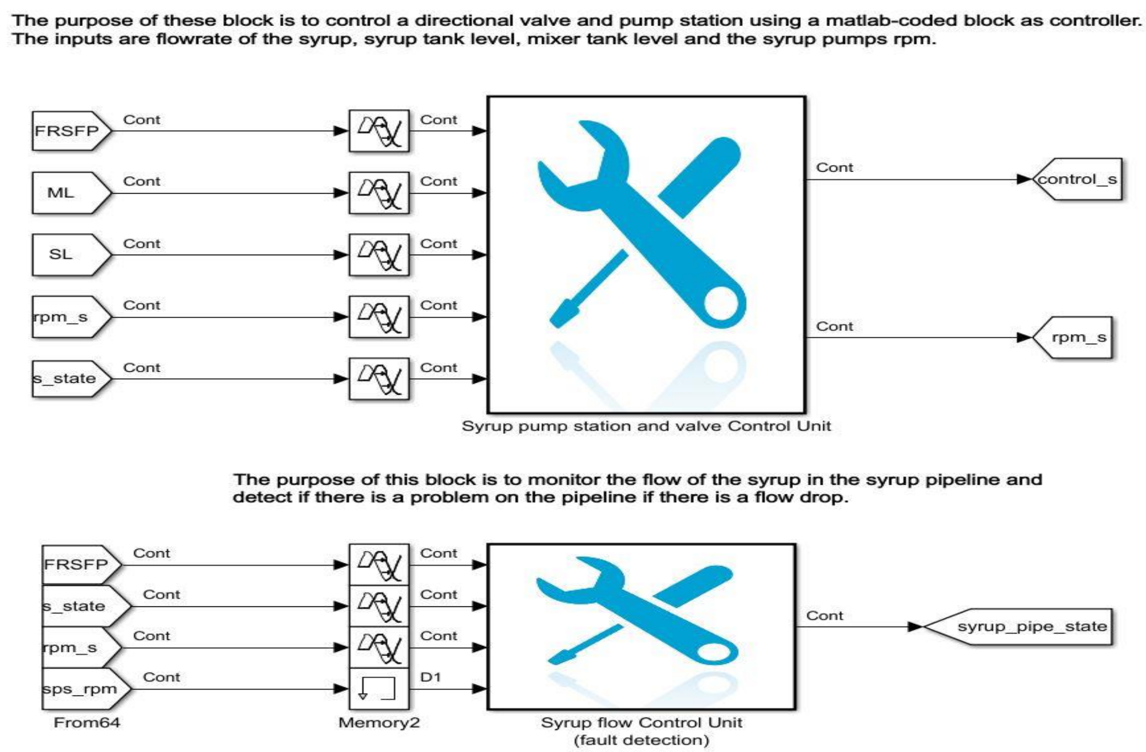


Figure 6.6 Simulink® Syrup pipeline Control units of the simulated PL

As it is illustrated in Figure 6.6, there are two control units for the syrup's pipeline operation. The first one like the water's flow controller monitors the syrup's flow and based on that can detect faults on the pipeline and the second one operates the pump station and control valve of the syrup pipeline.

In Figure 6.7 is presented the block diagram of the syrup flow control unit. The inputs are flow rate of the current syrup flow, the state of syrup pipeline, the current and the previous *rpm* values. This is a simple control unit responsible for monitoring the syrup flow of the pipeline.

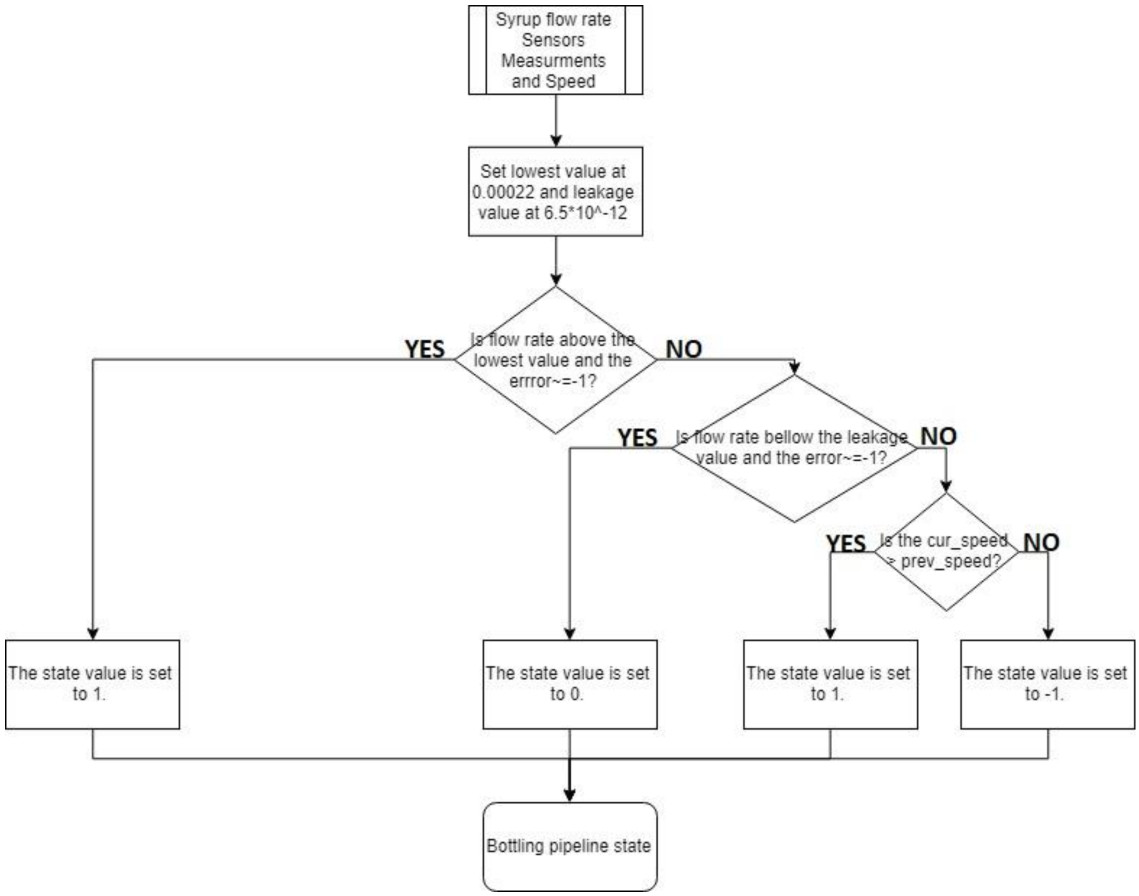


Figure 6.7 Boolean Control Algorithm for the syrup flow control unit

In Figure 6.8 is presented the block diagram of the water pump station and valve control unit. The controller's inputs are flow rate of the current syrup flow, the mixer and syrup tanks level, the speed of the pump station and outputs a control, a signal and *rpm* signals similar to the water control unit. The main difference between the syrup and water control units is that based on the recipe of the product the quantities and so limits are changed.

So Figure 6.4 and Figure 6.8 illustrate the main difference of the two controllers.

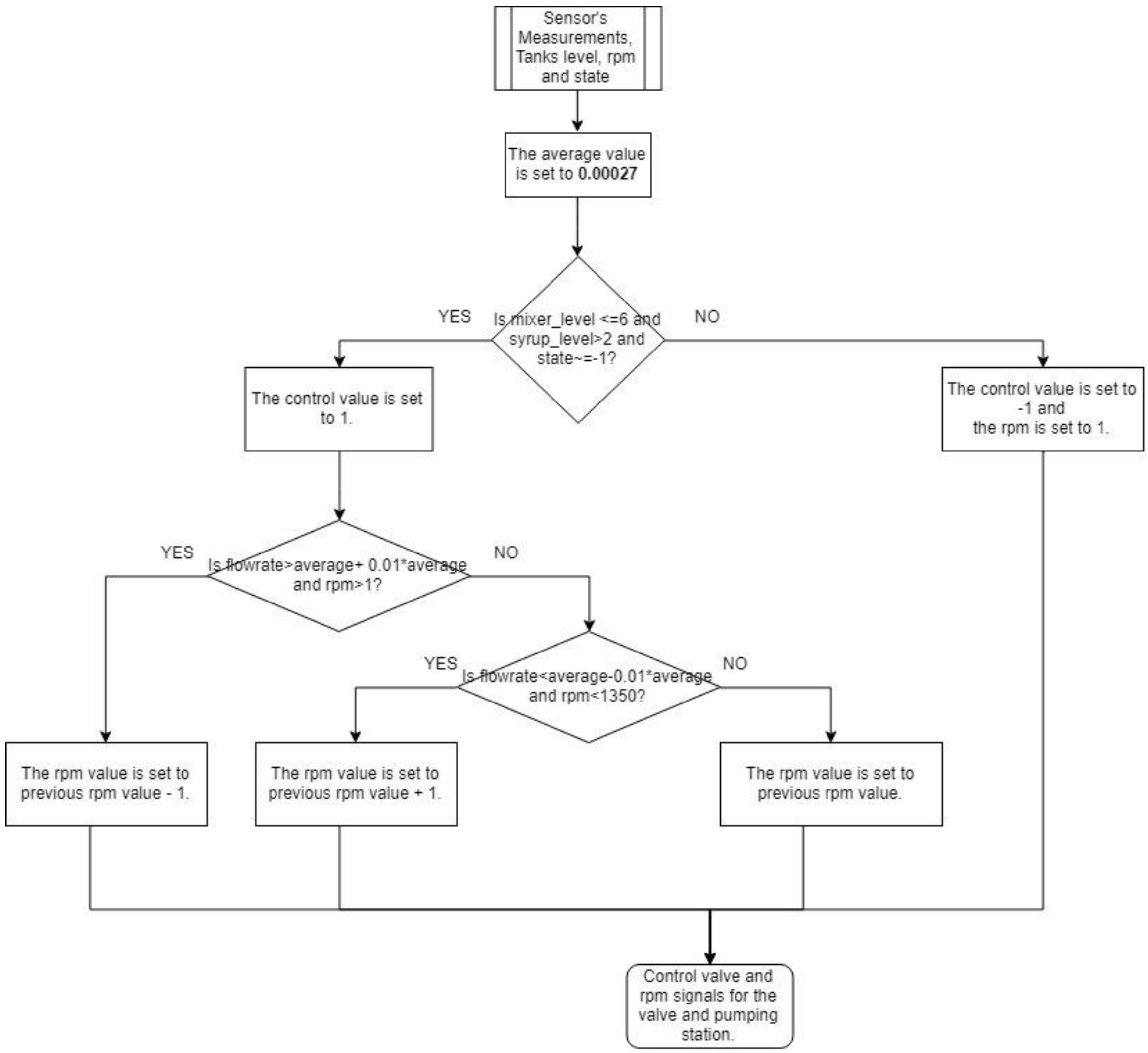


Figure 6.8 Boolean Control Algorithm for the syrup pump station and valve control unit

Based on the recipe and the production plant, the syrup controller has to supply with $1\ m^3$/*hour* of syrup for every $5\ m^3$/*hour* of water. So controller need to achieve the average flow of **0.00027** m^3/s.

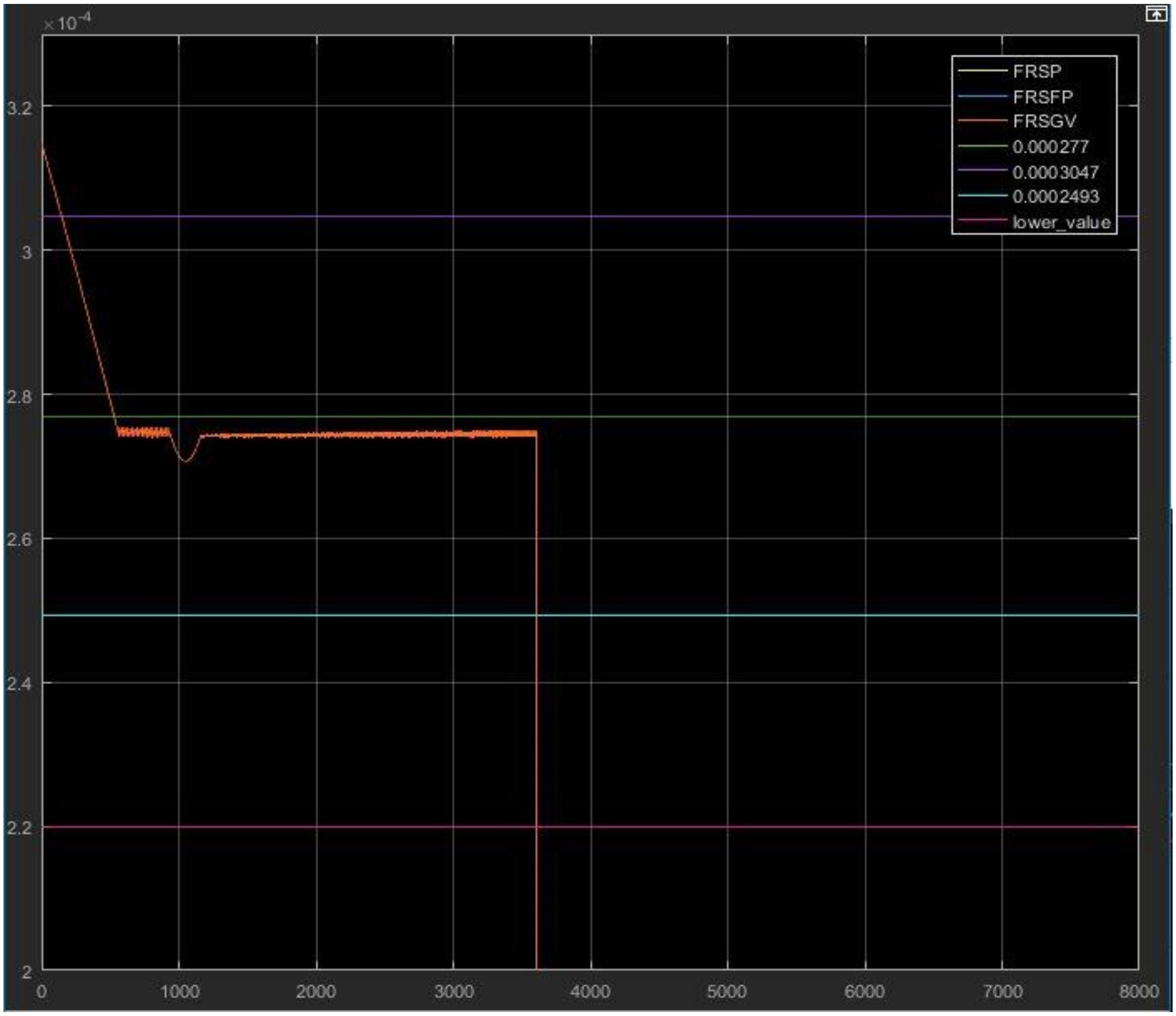


Figure 6.9 Simulation result. Flow rate diagram (m^3/s) vs time of the syrup system. The time axis is valued in sec (0 to 8000) and the flow rate axis is m^3/s (2 to 3.17*10^{-4}). Orange: of the system, purple: the upper value, green: the average value, cyan: lower value, red: lowest operation value.

The Figure 6.9 presents the flow rate diagram of syrup supply system. The time axis is valued in seconds and the flow rate axis is m^3/s. The target of the control unit is to maintain the flow at the operating range (between the upper and lower value) so that that mixer tank receives 1 m^3 of syrup in 1 hour. The current flow rate in the first 200 s is higher that the upper value due to pressure and the start of the process then it is stabilized at the average value until the manufacturing process is over and the operation of the syrup pipeline is suspended.

The Table 12 presents the diagram's colors providing a description as well as the values of each one.

Table 12 Colors description of the syrup flow diagram

DIAGRAM'S COLOR	DESCRIPTION	VALUE
ORANGE	The current flow rate	Current value
PURPLE	Upper value	$\mathbf{3.047*10^{-4}}\ m^3/s$
GREEN	Average value	$\mathbf{2.77*10^{-4}}\ m^3/s$
CYAN	Lower value	$\mathbf{2.493*10^{-4}}\ m^3/s$
RED	Lowest value	$\mathbf{2.2*10^{-4}}\ m^3/s$

6.2.3 Bottling pipeline Distributed Control Units of the simulated PL

As it is shown in Figure 6.10, same as the water and syrup, there are two control units for the bottling pipeline which are responsible for the final part of the production line. The first one is monitoring the flow on the bottling pipeline and the other is managing the pumping station and control valve.

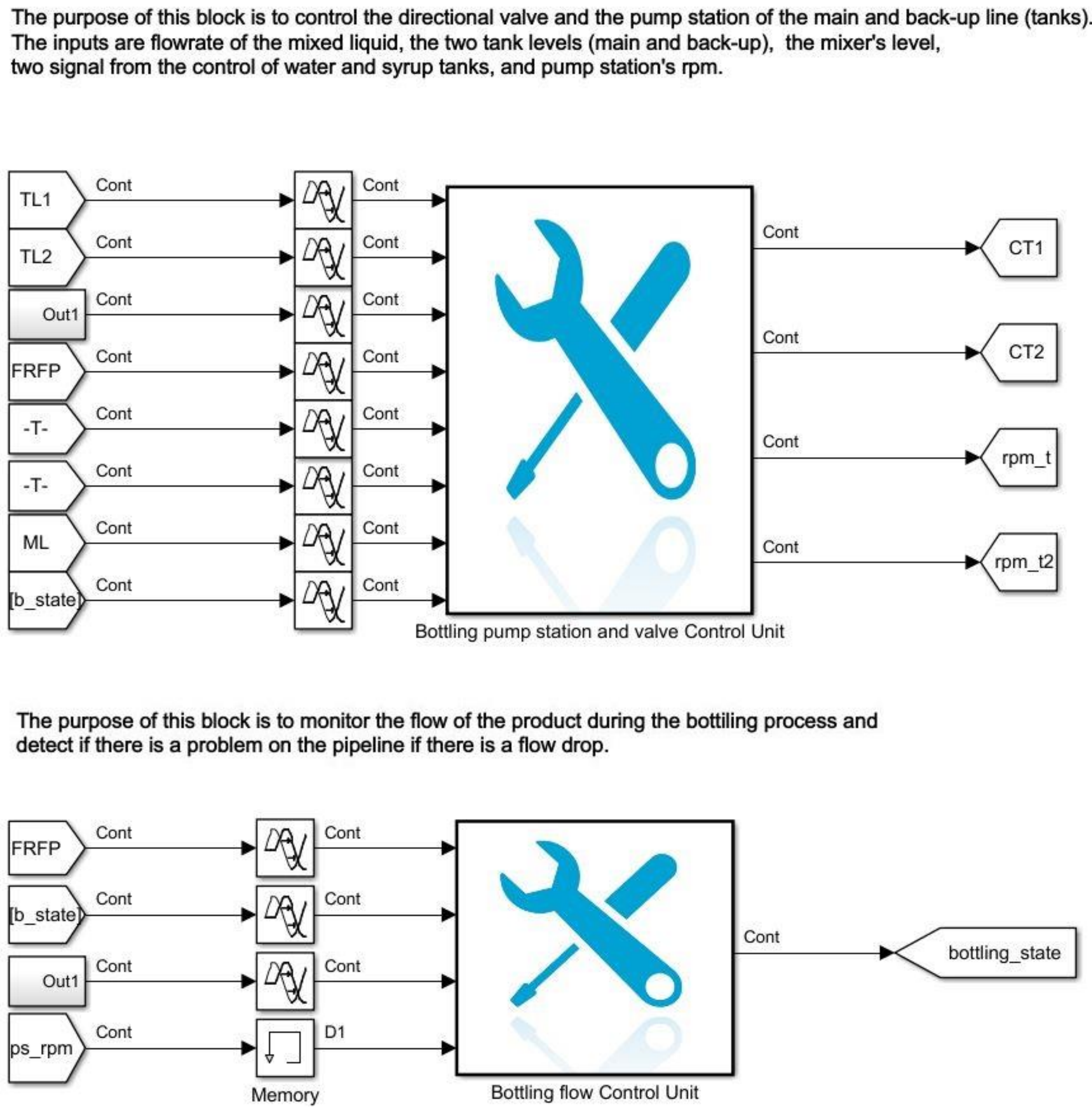


Figure 6.10 Simulink® Bottling pipeline Control units of the simulated PL

As it is presented in Figure 6.11, the block diagram of the bottling flow control unit. The controller's inputs are the current flow rate, the state of the bottling pipeline and the current and previous *rpm*.

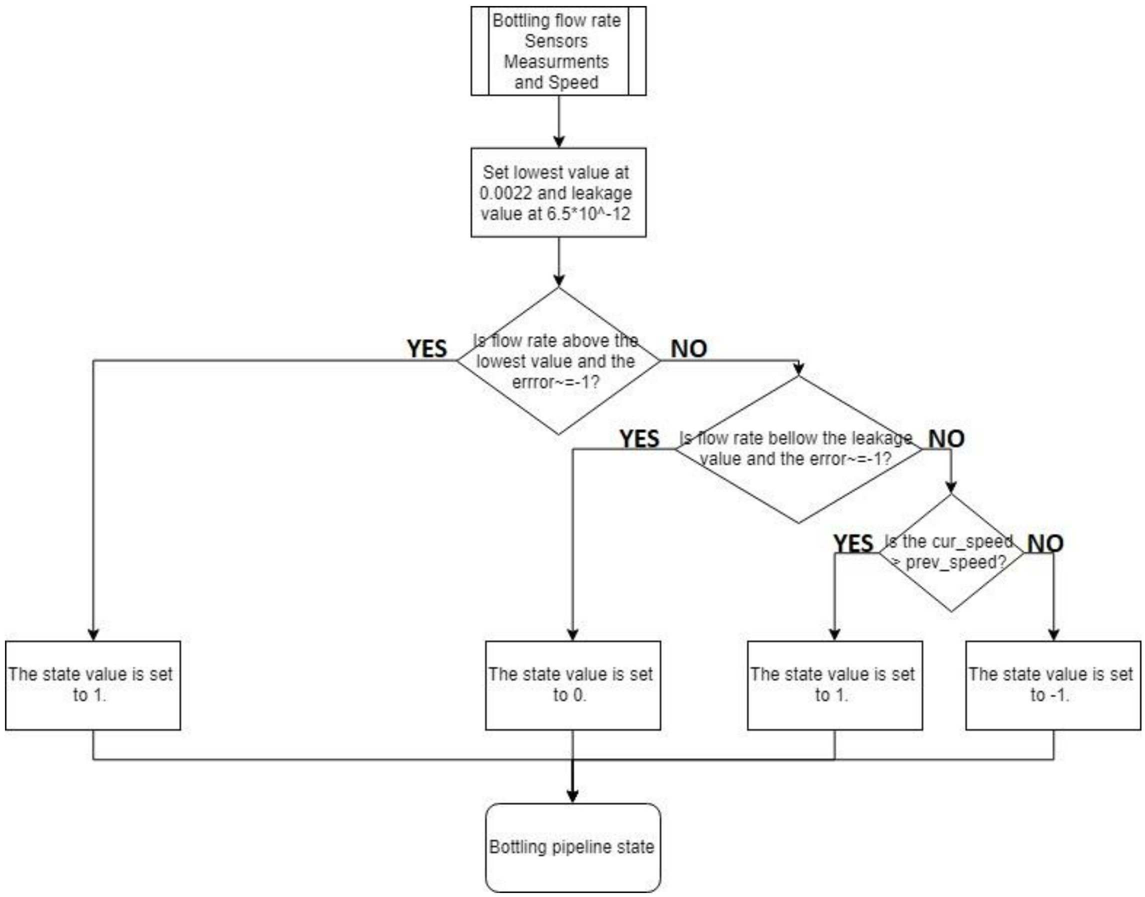


Figure 6.11 Boolean Control Algorithm for the bottling flow control unit

As it shown in Figure 6.12, the boolean control Algorithm for the control unit of the bottling process. Starting with inputs, the control unit has the main, backup tank's and mixers levels, the *rpm* which is pump's station speed, flow rate which is the current flow of the liquid and the two output signals of the previous control units. The outputs are the two control signals which manage the main and backup tank valve system.

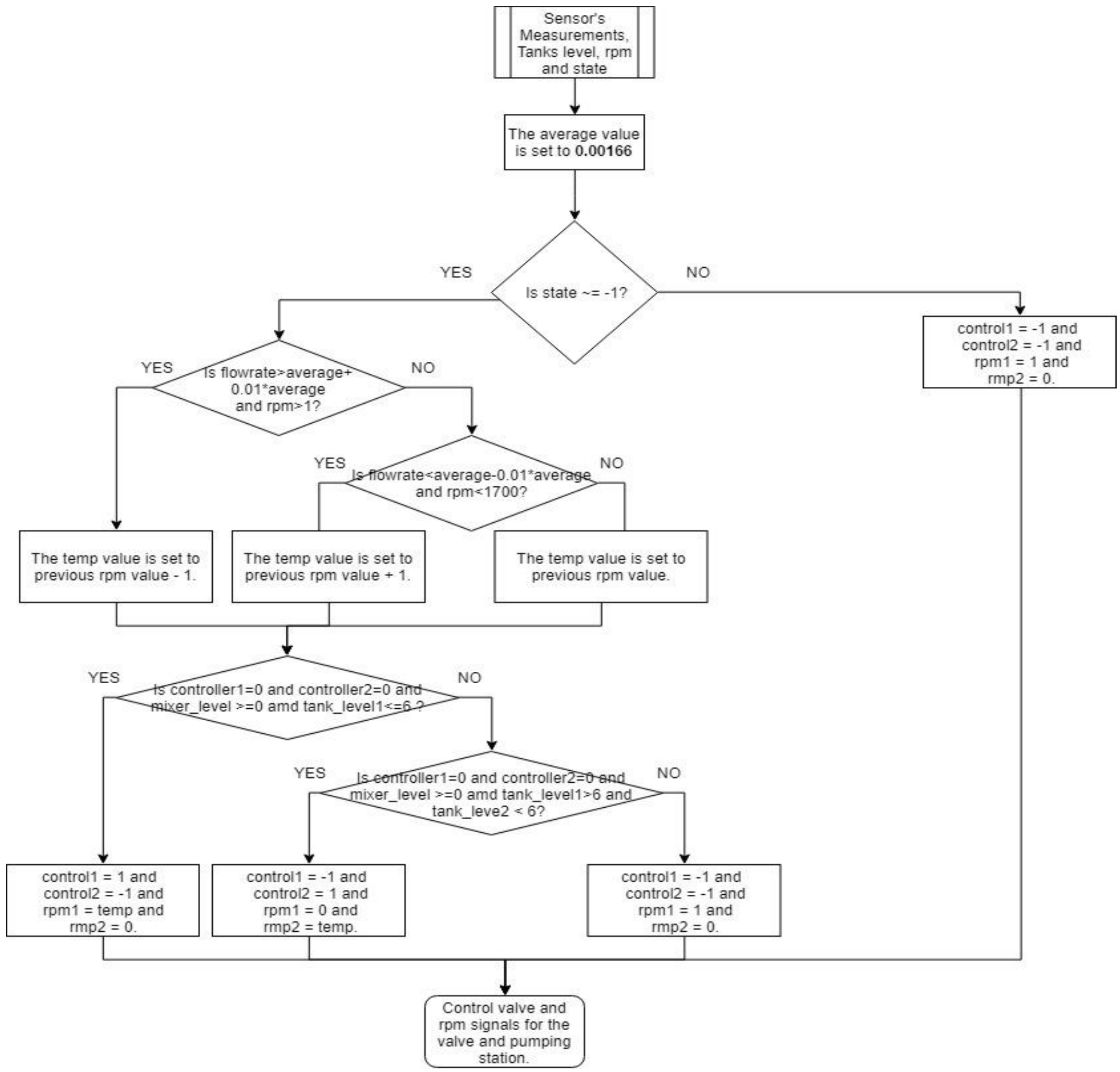


Figure 6.12 Boolean Control Algorithm for the bottling pump station and valve control unit

So if the system runs smoothly all the liquid flows from mixer to the main tank which represents the bottling process, otherwise if an error or problem occurs the controller transfers the liquid to the backup tank which represents a storage unit. For that reason, the controller needs to know the level of the tanks and mixer's.

Next, the two output signals are used to inform the controller that, mixer fills up with the right quantities of water and syrup, the mixing process is over and the bottling process starts. The flow rate signal is the current flow on the sub-system mixer-final tanks and the *rpm* is the current speed of the pump station.

The controller waits the manufacturing process to finish and when begins the process of bottling by first computing the lowest *rpm* for the final pipeline pump station. In order to do so, the controller analyzes the input data and change the value of the pumps speed on the fly every second. The result is that the flow rate that approaches the average value. To give an illustration, the production plant on ETANAP's SA factory is 6 m^3 of soft drink per hour, so the controller has to achieve an average flow rate about **0.00166** m^3/s.

As it represented in Figure 6.13 the flow of the pump station of the bottling pipeline, the controller manages an average flow rate of 0.00166 m^3/s.

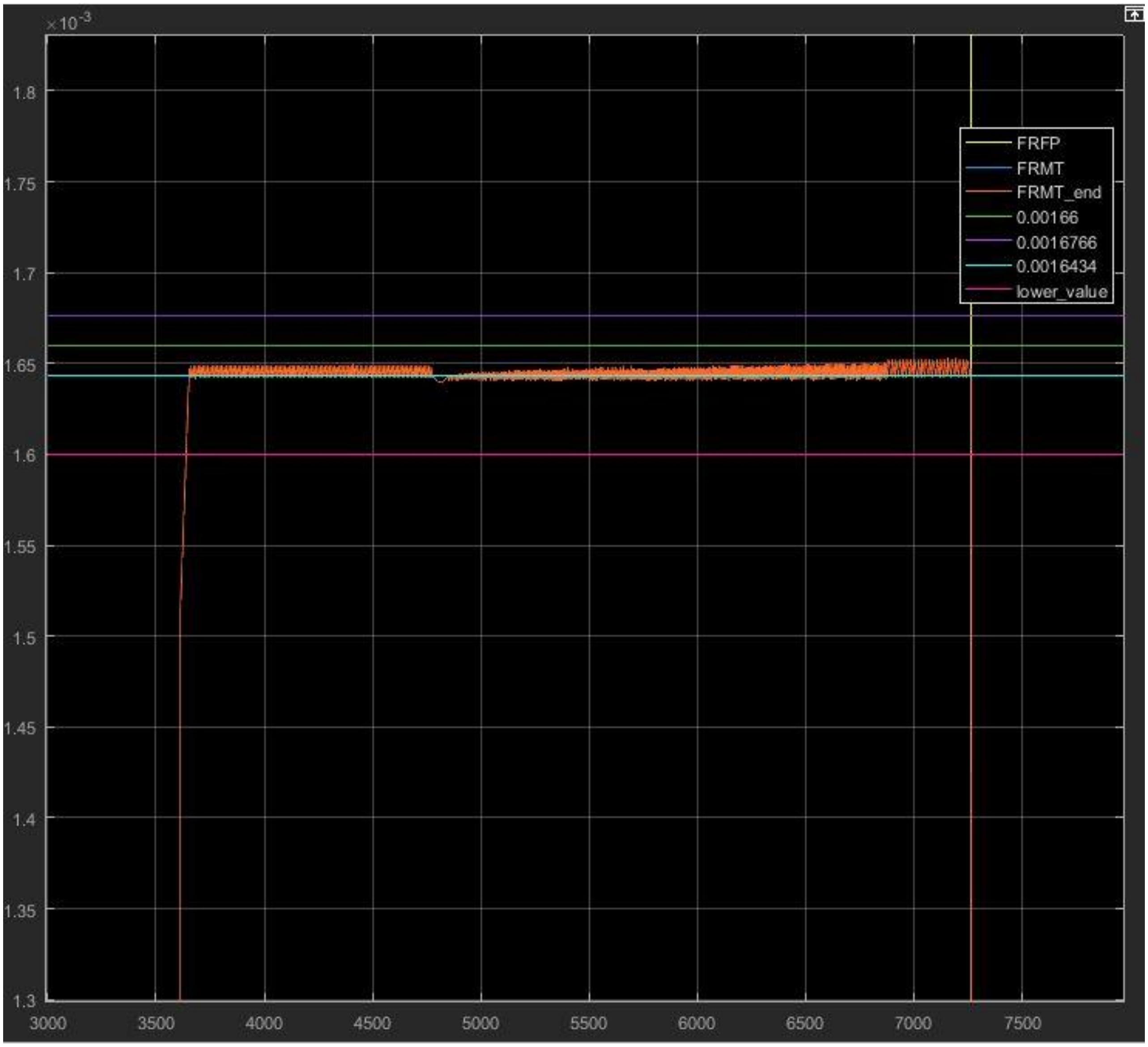


Figure 6.13 Simulation results. Flow rate diagram (m^3/s) of the bottling system. The time axis is valued in sec (3000to 8000) and the flow rate axis is m^3/s (1.2 to 1.75*10^{-3}). Orange: of the system, purple: the upper value, green: the average value, cyan: lower value, magenta: lowest operational value.

The time axis is valued in seconds and the flow rate axis is m^3/s. The target of the control unit is to maintain the flow at the operating range (between the upper and lower value) so that that bottling tank receives 6 m^3 of product in 1 hour. After the manufacturing process is over the bottling process starts while the current flow rate is raising and stabilized between the upper and lower values until the bottling process is done.

Having analyzed all the above, the controller has to compute the speed of the pumps, it starts by comparing the current flow with the average flow rate and if the result is within the limits then the controller doesn't change the speed and the pumps operate at steady *rpm*. On the other hand, if the result is out of the operating range then the controller increases or decreases the speed respectively.

The

Table 13 presents the diagram's colors providing a description as well as the values of each

DIAGRAM'S COLOR	DESCRIPTION	VALUE
ORANGE	The current flow rate	Current value
PURPLE	Upper value	**1.6766*10**$^{-3}$ m^3/s
GREEN	Average value	**1.66*10**$^{-3}$ m^3/s
CYAN	Lower value	**1.6434*10**$^{-3}$ m^3/s
MAGENTA	Lowest value	**1.6*10**$^{-3}$$m^3/s$

one.

Table 13 Colors description of the bottling flow diagram

DIAGRAM'S COLOR	DESCRIPTION	VALUE
ORANGE	The current flow rate	Current value
PURPLE	Upper value	**1.6766*10**$^{-3}$ m^3/s
GREEN	Average value	**1.66*10**$^{-3}$ m^3/s
CYAN	Lower value	**1.6434*10**$^{-3}$ m^3/s
MAGENTA	Lowest value	**1.6*10**$^{-3}$$m^3/s$

6.2.4 Production state Control Unit of the simulated PL

The seventh control unit of the simulated PL of Figure 6.14, is a MATLAB®-based function which manages the production state of the individual pipelines. The individual control units are responsible for the individual operation of their pipelines but if there is a problem or error which the responsible control unit can't handle the rest of the production line need to be suspended. The production state control unit is responsible for the good operation of the PL and connects the individual control systems.

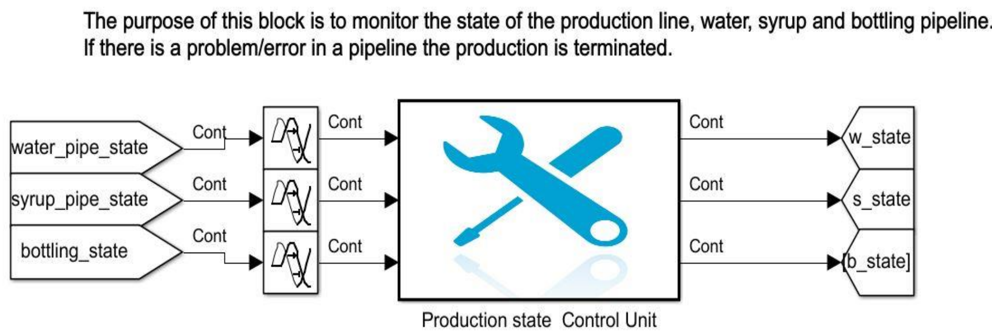


Figure 6.14 Simulink® Production state Control unit of the simulated PL

The Figure 6.15 presents the block diagram of the production state control unit. The controller's inputs are the water, syrup and bottling pipeline state values.

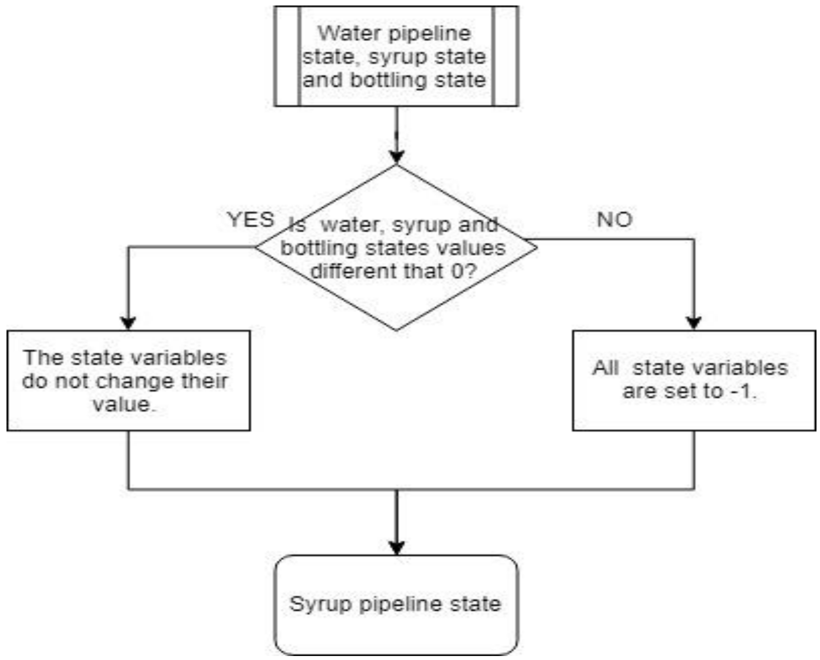


Figure 6.15 Boolean Control Algorithm for the production state control unit

6.3 Conclusions

In conclusion, in this chapter presented the structure of the control units of the PL system based on DCS, ID and MAS approaches. For the optimal design of the control system the simulated PL is divided into three pipelines (the water, syrup and bottling).

Then discussed and analyzed the operation and design of the control system which consists of seven Boolean logic control units which have the responsibility to operate a part of the production line. Each pipeline controlled and monitored by two control units, the first monitors the flow rate based on the sensors to define the pipeline's state and the second one controls the field devices (i.e. pumping station and valves).

After designing the control system, were presented the flow rate vs time diagrams, how the control units manage the simulated PL system and it is verified that the simulation model is stable under different operation cases.

Next, the CHAPTER 7 will present how the system performs, operates in time or when a problem occurs and show the results for different simulated operation case studies.

CHAPTER 7. SIMULATION RESULTS OF DCS CONTROL APPLIED ON PL OPERATION FOR DIFFERENT SCENARIOS

Having analyzed the data and materials of a soft drink PL in CHAPTER 4, introduced the design of the a soft drink PL in CHAPTER 5 and then suggested a distributed control system based on DCS and MAS approaches in CHAPTER 6. This chapter is going to demonstrate the simulation results of the behavior of the PL for different operation scenarios of the pumping station as it is controlled by the simulated DSC system.

As we mentioned in subchapter 5.1, the use of dynamic simulation and simulation tools provide the engineers the ability to test their model's behavior effectively and efficiently. Modeling and simulation of complex production systems aim at increasing the understanding of the system. The advantages of such models are the capability to test complex real-life systems. Another benefit is that the engineers can test different scenarios without intervening in the real life system.

So this chapter is going to focus on the results of three different scenarios which simulate operating situations in order to test the efficiency of the DCS system and the system's behavior.

So the subchapter 7.1 Scenario #1 is going to simulate the operation of the system where the plant operates under normal nominal conditions.

Next, in subchapter 7.2 Scenario #2 is going to test the system's behavior in the situation where one pump of the water pump station is malfunctioning.

Lastly, in subchapter 7.3 Scenario #3 is going to test the system's behavior in the situation where two of the three pumps are faulty.

7.1 Scenario #1: Production process operates under normal, nominal condition

This subchapter presents the behavior of the system as it is running normal. This means that the production line is working perfectly and all the components are functioned normally.

In this scenario the process starts with the manufacturing/mixing process (in Figure 5.5 is shown in Block diagram the manufacturing process of the simulated PL) which is the process where the mixer tank is filling with 6 m^3 of syrup and water. The water and syrup pump stations, control valves and sensors are functional meaning that all of them are operational and they are sustaining the water and syrup flow and pressure at the desired levels. Based on the production plant the manufacturing process lasts almost an hour. Throughout the manufacturing process the pump station is been regulated by the water pump controller to maintain an average value of the flow rate at **0.001388** m^3/s without operating the pumps at high *rpm* if it's not necessary (in Figure 6.5 is shown the flow rate diagram of the water pipeline).

The same thing is implemented on the syrup pipeline and pump station, the syrup controller maintain the average value of the flow rate at **0.000277** m^3/s (in Figure 6.9 is shown the flow rate diagram of the syrup pipeline).

The manufacturing process follows the recipe which is mentioned on previous chapters providing $\mathbf{6*10^3}$ *lt* of soft drink. And so the manufacturing process is over and the product is entering the bottling process (see Figure 5.6 is shown in Block diagram the bottling process of the simulated PL). In this stage of the process the final product is transferring to the bottling machine which in our model is simulated by a tank.

The production process information for the capabilities of our simulated system regarding the manufacturing and bottling processes are presented in Table 14.

Table 14 Manufacturing and Bottling process details of the simulated PL which has all the components running normal

PROCESS	DESCRIPTION	PRODUCTION CAPACITY	BOTTLES CAPACITY	TIME
MANUFACTURING	Filling the mixer with $\mathbf{5*10^3}$ *lt* of water and $\mathbf{1*10^3}$ *lt* of syrup.	$\mathbf{6*10^3}$ *lt of soft drink*	-	**1** *hour*
BOTTLING	Filling the tank-PET type or glass bottles.	**18,182** *bph* or $\mathbf{12*10^3}$ *bph* or $\mathbf{24*10^3}$ *bph*	**0.33** *lt* or **0.5** *lt* or **0.25** *lt*	**1** *hour*

During the bottling process the bottling controller manages the pipeline, valves and pump station to sustain the average value of flow rate at **0.00166** m^3/s operating the pumps as efficient as possible (in Figure 6.13 is shown the flow rate diagram of the bottling pipeline).

Throughout the simulation, the DCS is monitoring and managing the speed of three pumps station, the flow rate of the system and the pressure. In Figure 7.1 it is presented the speed of the system's pump stations. As is shown in Figure 7.1 as well as Figure 6.5, Figure 6.9 and Figure 6.13, the manufacturing process lasts for **1** *hour* or to be exact **3605.2** *s*, at this time the manufacturing process was ended and the mixer tank was filled with $\mathbf{6*10^3}$ *lt* of soft drink. Moreover, the bottling process started **5** *s* later at **3610.2** *s* and finished an *hour* later or **3652.4** *s.* As a result during the bottling process the simulated distributed system managed to bottle $\mathbf{6*10^3}$ *lt / hour* supporting the results displayed in Table 14.

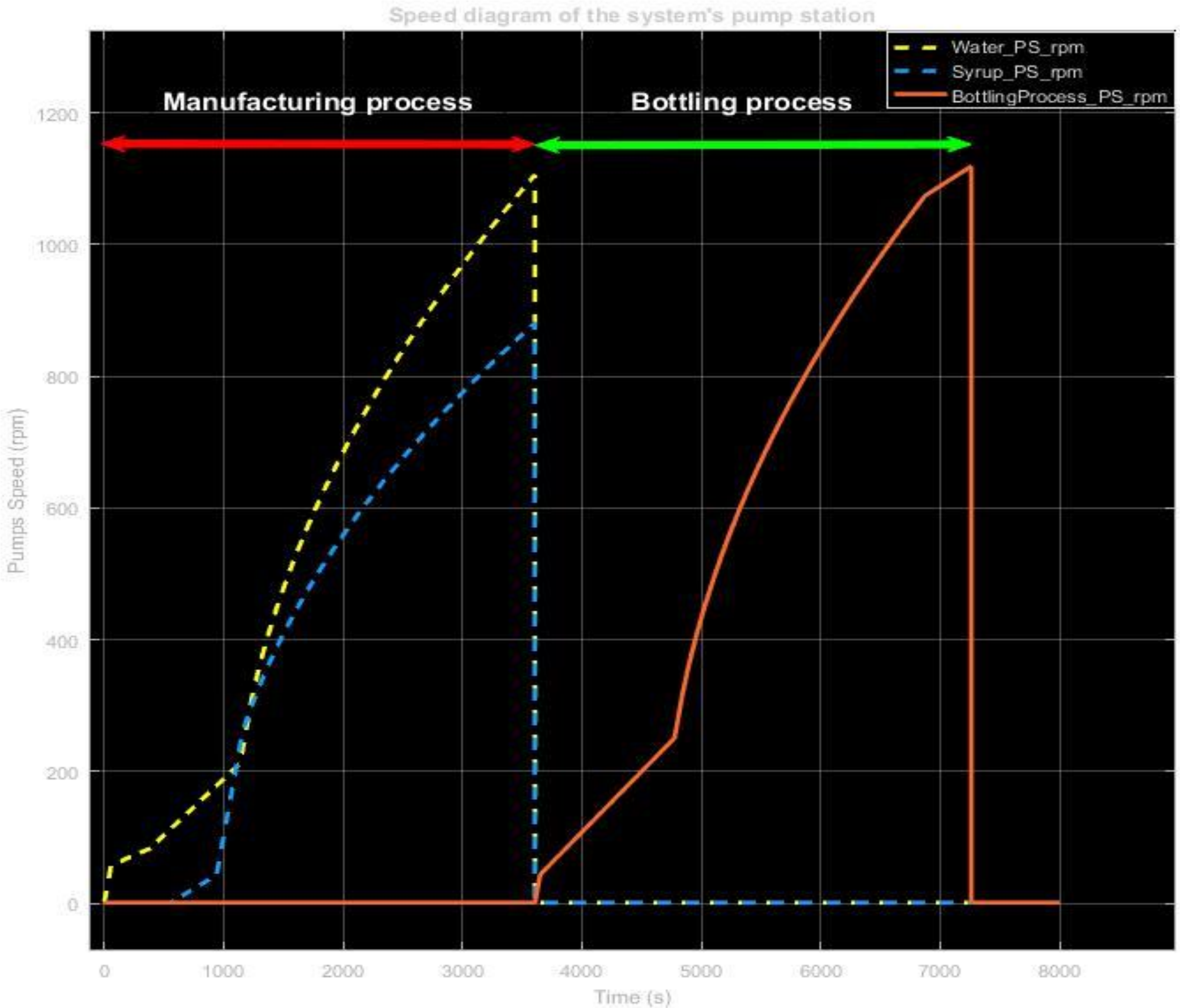


Figure 7.1 Simulation result of scenario #1. Speed (rpm) vs time diagram of the system's pump stations. Orange: of the system, purple: the upper value, green: the average value, cyan: lower value.

7.2 Scenario #2: Malfunction of one of the three pumps in water pump station

The last subchapter presented the experimental results of the system simulation as the production line was operational and every component of the production line was functional. This subchapter focuses on a scenario in which a malfunction is occurred on the production and how the control system would respond.

There are many different scenarios and problems that can be simulated. During the manufacturing or bottling process, it is possible the control unit to encounter different types of problems such as pump(s) malfunction, sensor or valve problems or even a pipeline failure. This scenario focuses on the malfunction of a single pump of the water pump station and the respond of the control unit. So the control unit regulate the remaining pumps to stabilize the flow rate.

The Table 15 presents the production results of our simulated PL using the two out of three operational water pumps. The control system manages to produce the same results having no delay finishing the manufacturing process.

Table 15 Manufacturing and Bottling process details of the simulated PL which has a water pump malfunction

PROCESS	DESCRIPTION	PRODUCTION CAPACITY	BOTTLES CAPACITY	TIME
MANUFACTURING	Filling the mixer with $\mathbf{5*10^3}$ *lt* of water and $\mathbf{1*10^3}$ *lt* of syrup.	$\mathbf{6*10^3}$ *lt of soft drink*	-	**1** *hour*
BOTTLING	Filling the tank-PET type or glass bottles.	**18,182** *bph* or $\mathbf{12*10^3}$ *bph* or $\mathbf{24*10^3}$ *bph*	**0.33** *lt* or **0.5** *lt* or **0.25** *lt*	**1** *hour*

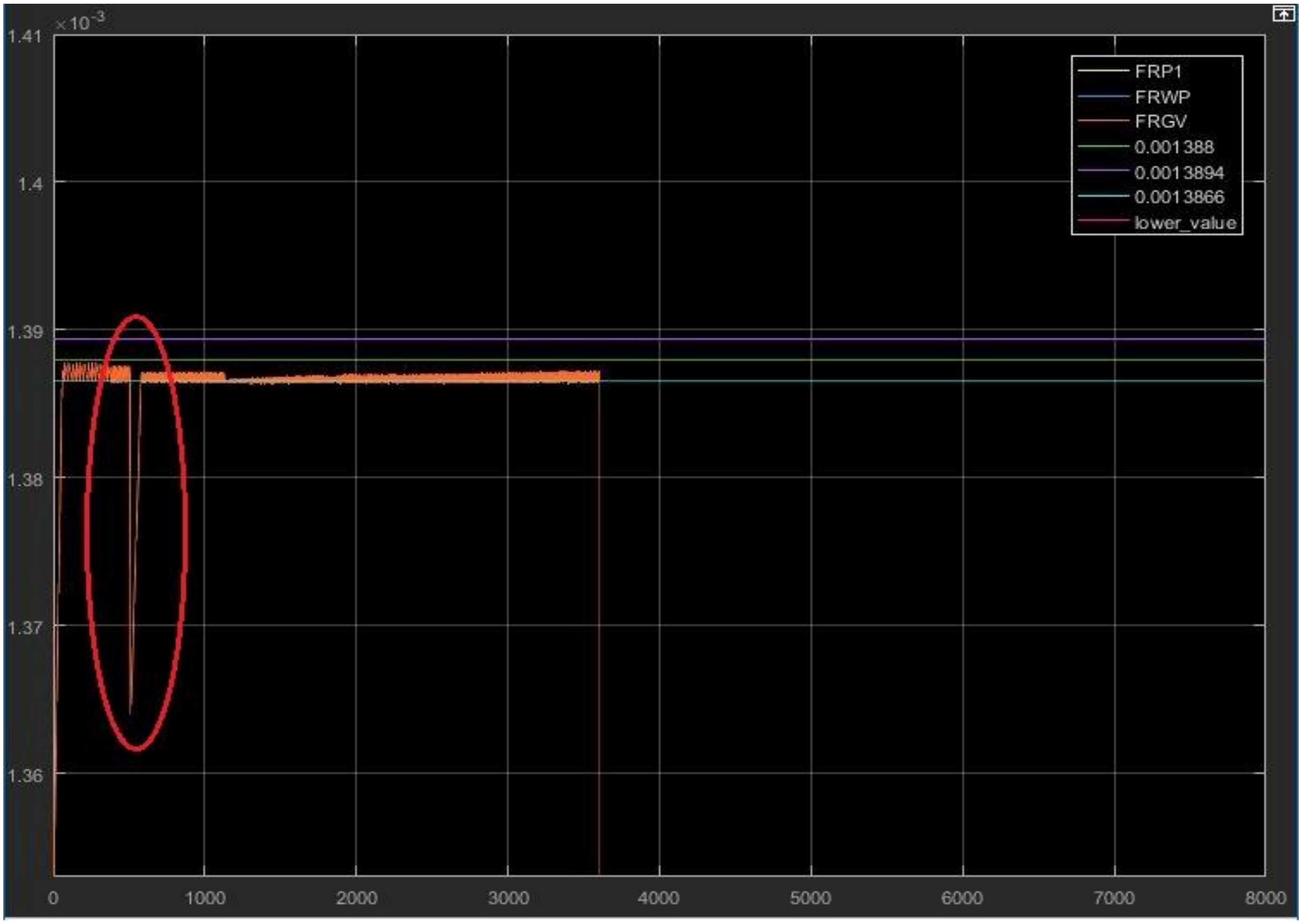


Figure 7.2 Simulation results of the scenario #2. Flow rate diagram of the water pipeline, working two pumps after a certain time.
The time axis is valued in sec (0 to 8000) and the flow rate axis is m^3/s (1.35 to 1.41*10^{-3}).
Orange: of the system, purple: the upper value, green: the average value, cyan: lower value, red: lowest operational value.

Initially, at t=0 s, the simulation starts having the water and syrup tanks in their maximum capacities (20 m^3 and 3 m^3 respectively) and the remaining three tanks empty. As it illustrated in Figure 7.2 at 510 *s* the water pump station has a malfunction in one of the three pumps, **see red ellipse**, so the flow rate of the water pipeline is reduced. The water pipeline DCS manages the flow drop by regulating the remaining two pumps at higher *rpm* and after **70** *s* the water flow is stabilized in the operating range.

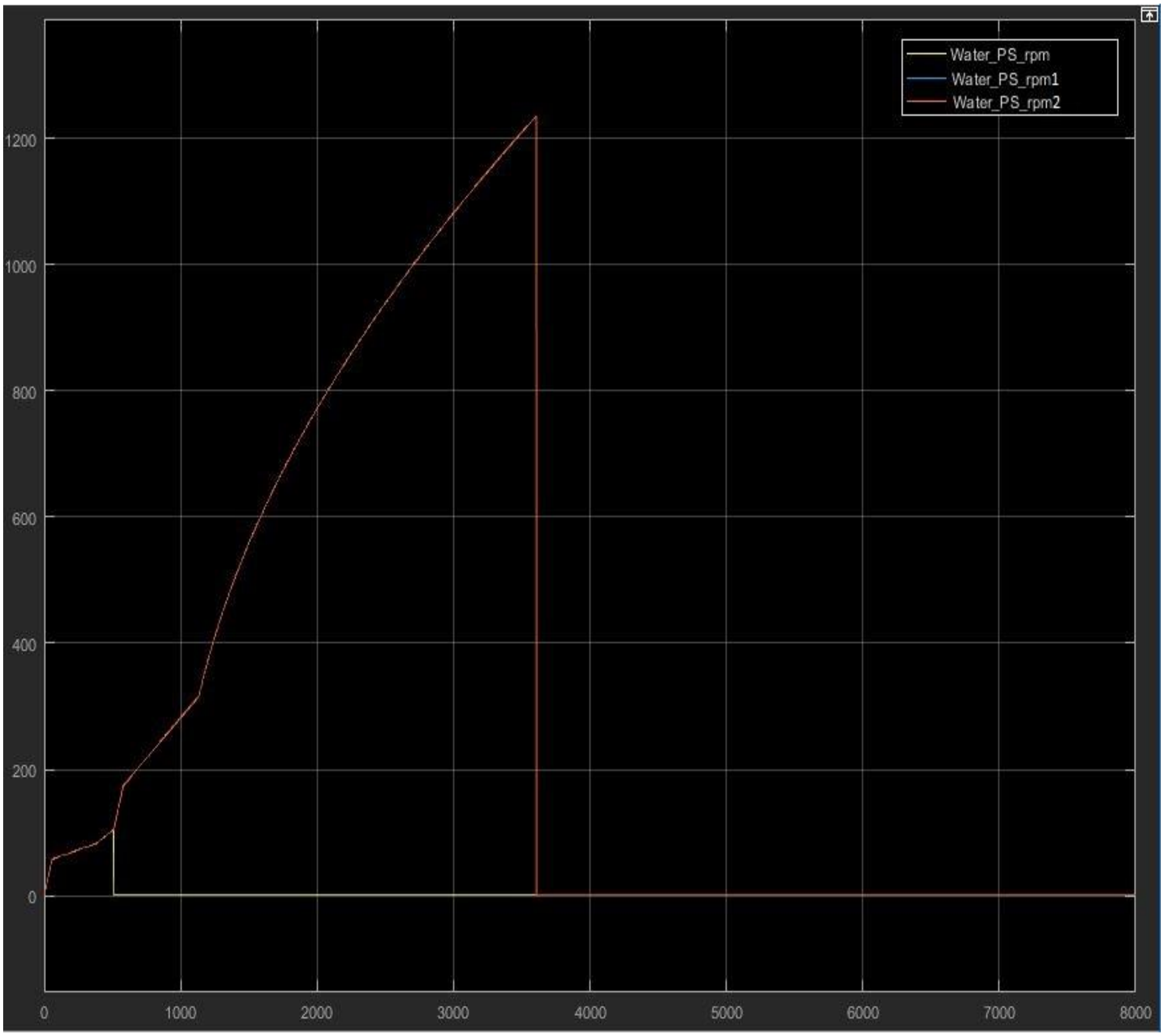


Figure 7.3 Simulation result of the scenario #2. Speed diagram of the water pump station with a malfunction of one pump.
The time axis is valued in *s* (0 to 8000) and the speed axis is *rpm* (0 to 1300).
Orange (as well as blue): the two operational pumps, yellow: the non-functional pump.

The Figure 7.3 presents the speed diagram of the water pump station and shows the rapid speed change of the two remaining pumps in order to regulate the flow drop and the shutdown of the third pump.

According to the capabilities of the PL in Table 15, the simulation results in Figure 7.2 and Figure 7.3, we conclude that the proposed control system, see subchapter 6.2.1, of the water pipeline manages the flow drop because of the non-functional pump using the remaining two pumps in higher *rpm*. As consequence, the flow rate, after **70** *s* is stabilized at the operating range. The production process continues finishing the manufacturing process after **3608.4** *s* and starting the bottling process at **3611** *s.* As a result during the bottling process the simulated distributed system managed to bottle $\mathbf{6*10^3}$ *lt / hour* or **3655** *s* which is almost similar with the results of the Scenario #1: Production process operates under normal, nominal condition proving the results of Table 15 Manufacturing and Bottling process details .

The simulation shows that the designed DCS manages an unexpected flow drop caused by a pump malfunction, stabilizes the water pipeline's flow in **70** *s* and continues the production operation of the soft drink PL.

7.3 Scenario #3: Malfunction of two of the three pumps in water pump station

The previous subchapter presented the experimental results of a single pump malfunction and the response of the control unit to the problem. This subchapter presents a slightly different scenario which is that during the manufacturing process two pumps malfunction resulting the termination of their operation as well as the termination of entire production process for safety reasons. This is really important decision because if the damage or malfunction is not crucial the production should continue the operation else if the damage is critical to terminated the production process securing the factory's machinery.

Initially, at t=0 s, the simulation starts having the water and syrup tanks in their maximum capacities (20 m^3 and 3 m^3 respectively) and the remaining three tanks empty. As it illustrated in Figure 7.4 as well as in Figure 7.5, at 166 *s* the water pump station has a malfunction in one of the three pumps, **see first red ellipse**, so the flow rate of the water pipeline is reduced. The water pipeline DCS manages the flow drop by regulating the remaining two pumps at higher *rpm* and after **59** *s* the water flow is stabilized in the operating range. After that, at **1402** *s* of the simulation, the system loses a second water pump, **see second red ellipse**. Considering the fact that the system uses the last pump to supply the water needed for the production manages the flow drop using the last water pump at the highest *rpm* possible, the time interval which the water's flow is stabilized is **680** *s*. Then the water flow is in operating range for **343** *s* until its starts dropping at **2425** *s* and finally terminated after **774** *s* at **3199** *s* of the simulation

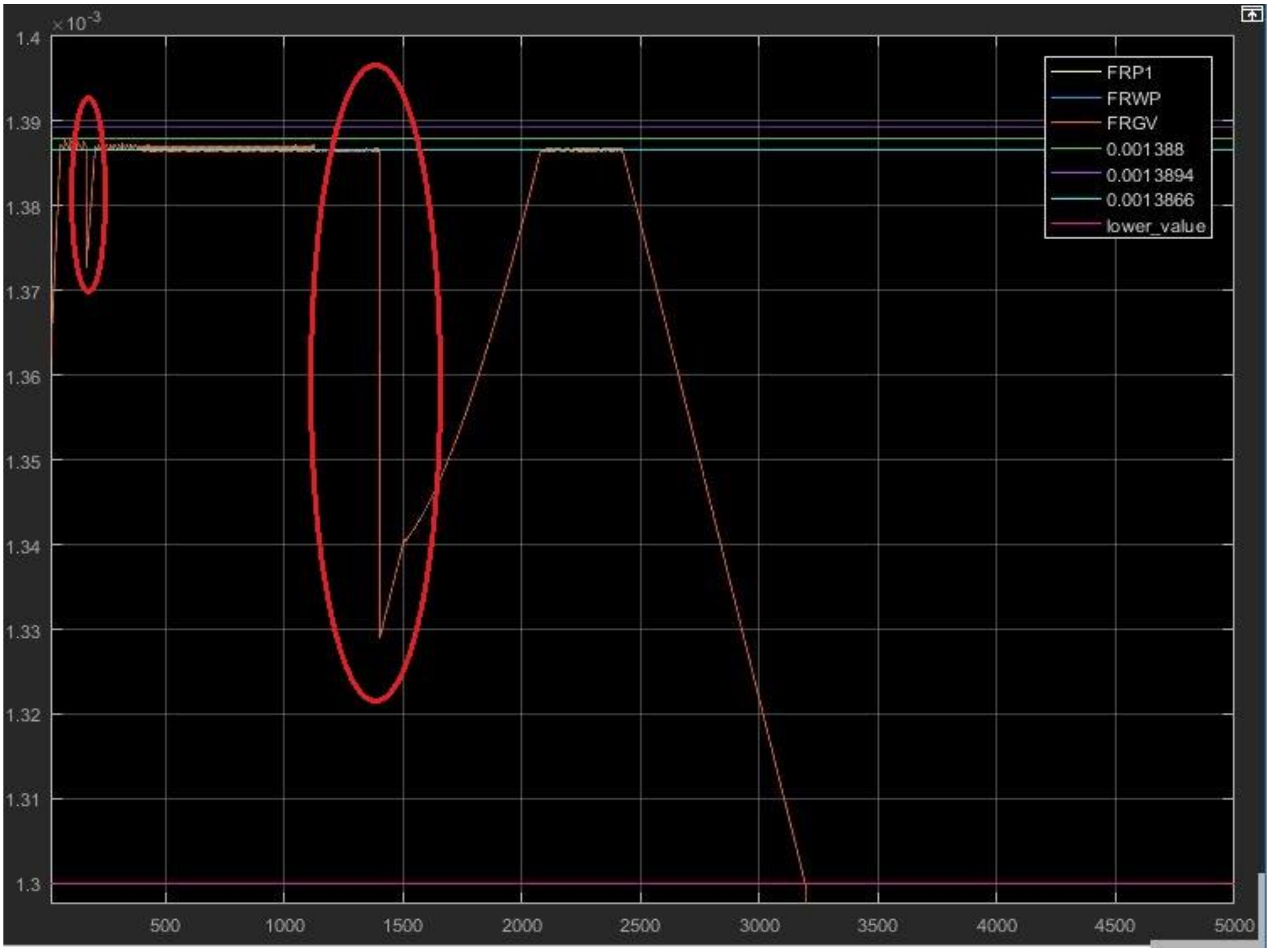


Figure 7.4 Simulation result of scenario #2. Flow rate diagram of the water pipeline, working with only one pump after a certain time.
The time axis is valued in sec (0 to 5000) and the flow rate axis is m^3/s (1.3 to 1.4*10^{-3}).
Orange: current flow rate, purple: is the upper value, green: the average value, cyan: the low value, red: the lower error value.

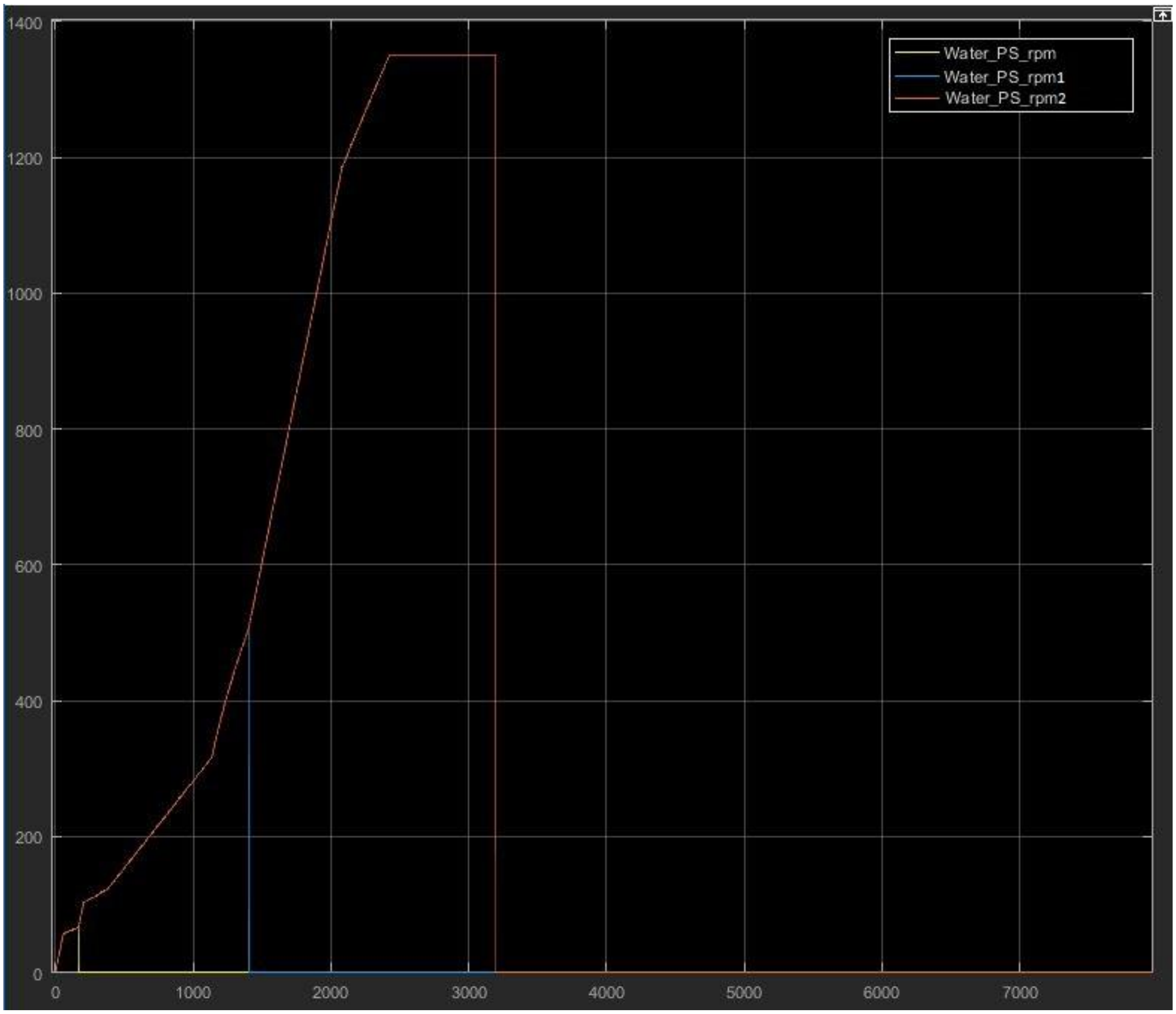


Figure 7.5 Simulation result of the scenario #3. Speed diagram of the water pump station with one operational pump.
The time axis is valued in *s* (0 to 8000) and the speed axis is *rpm* (0 to 1400).
Orange (as well as blue): the two operational pumps, yellow: the non-functional pump.

This proves that the control system manages the first malfunction by regulating the remaining pumps and stabilize the flow at the operating range (like in Scenario #2: Malfunction of one of the three pumps in water pump station) providing that the system can handle the loss of one pump for **1197** *s* but when the second malfunction occurred at **2082** *s*, the control system evaluate the performance of the system and terminates the operation of the PL after the **3199** *s* following the safety protocols.

7.4 Conclusions

This chapter focuses of three simulation scenarios and presented the system's behavior based on different scenarios. Each simulation scenarios lasts **8000** *s* which is more than enough time for the system to finish the production. First of all, the Scenario #1 described the functional behavior of the system which every part of it is operational without any errors. The PL is under normal operation which means that the PL is providing a stable fluid flow. The manufacturing process is completed within **3605.2** *s* or covering the **45.06%** of the simulation time and the bottling process **3652.4** *s* or **45.7%** of the simulation time. As a result, design DCS manages to bottle $\mathbf{6*10^3}$ *lt per hour*.

Next, Scenario #2: Malfunction of one shows that the designed DCS manages an unexpected flow drop caused by a pump malfunction. The DCS stabilizes the water pipeline's flow after **70** *s* or **0.87%** completing the manufacturing process in **3608.4** *s* or **45.1%** of the simulation time. As a result, the time difference in manufacturing process between the two simulating scenarios is almost **0.04%** of the simulation time or **3.2** *s*. The production operation of the soft drink PL terminates after bottling $\mathbf{6*10^3}$ *lt per hour*.

Lastly, Scenario #3: Malfunction of two of the three pumps in water pump station described the behavior of the system having a crucial problem in the water pumping station leading to the abortion of the PL's operation. The control system manages the first malfunction by regulating the remaining pumps and stabilize the flow at the operating range (like in Scenario #2: Malfunction of one of the three pumps). The system was stabilized in the operational range for **1197** *s* but when the second malfunction occurred, the control system evaluate the performance of the system and terminates the operation of the PL after the **3199** *s* of the simulation, covering the **40%** for the simulation time, following the safety protocols.

CHAPTER 8. INTRODUCING MPC CONTROL IN A DCS FOR A SOFT DRINK PRODUCTION LINE

The development of an advanced control system is crucial for the manufacturing industries. One approach developing such systems is by designing and incorporating strategies in a DCS, such as MPC, which can optimal manage many significant processes such as bottling and packaging of the products or control the production process (manufacturing control).

8.1 The applications of the MPC approach on a soft drink production line

The MPC approach is a rather useful technology that is implemented on various industries such as process industries for years. Based on the work [4] and [5] and in Figure 2.1, there are different manufacturing divisions presented in Table 16:

Table 16 Factory manufacturing divisions

Division	***Implementation***
Field	Contains the field devices such flow, pressure sensors or control valves
Direct control	Contains the I/O modules and their distributed electronic processors
Plant Supervisory	Contains the supervisory computers
Production control	Contains the computers for monitoring the production and targets
Production scheduling	Contains the computers which are directly control the production

So based on that, the levels can be used to describe the different controlling level of the production line. This subchapter presents two applications of a MPC approach on a soft drink production line.

8.1.1 MPC Application #1

Designing a control system and embedded it into a production plant is a challenging problem. According to Figure 2.1 and Figure 8.1, the control management can be done designing levels of control systems which every level have to address a certain task. As illustrated in Figure 8.1.

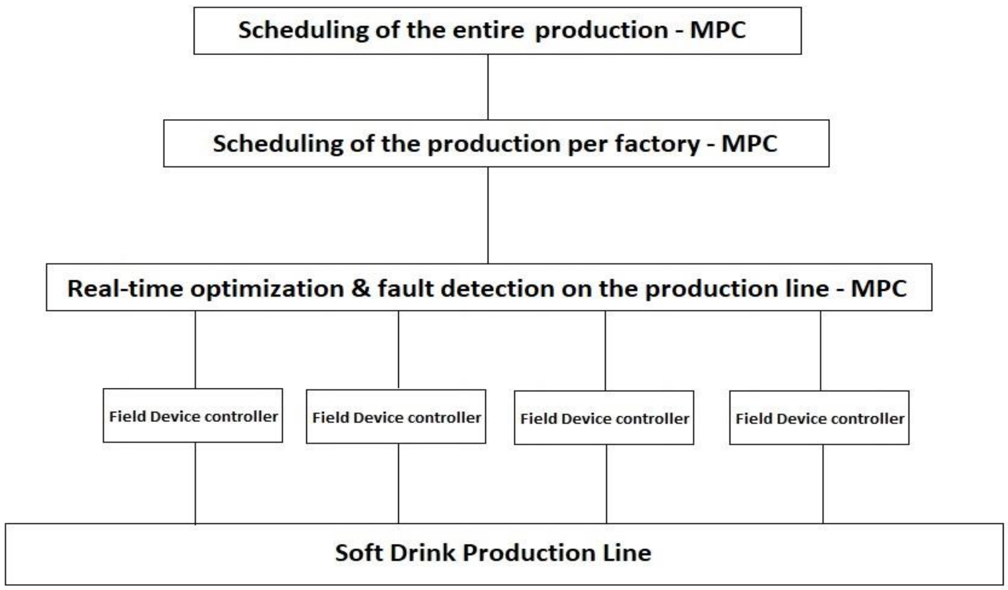


Figure 8.1 Control levels of a soft drink company

The scheduling of the entire production is crucial on a big scale company with many factories and different production plants as well as shipment to different countries. Typically, soft drink companies receive their orders daily so they have to manage the segmentation of the production per factory. A solution to that could be the use of a MPC algorithm which can manage the segmentation. The controller's input would be the order of the product or products, the location of the factories, the daily production per factories. So the MPC should analyse these inputs to decide the segmentation of the production. The MPC algorithm could run by a server in which every factory as well as the HQ of the company will be connected.

Every factory needs to adapt its operation according to the production segmentation. So the control system of the factory's production plants needs to decide about the configuration of the production line(s) as well as update the server about the production process. Then, a real time optimization and fault detector is monitoring the production the production line. The task of this control system is to monitor the field device and their controller to optimize their operation as well as to detect any malfunction on the system. A MPC approach could be appropriate because MPC output are based on future prediction which can be crucial for optimization and fault detection.

Lastly, the field device controller are responsible of the operation of the field devices such as control valves, tanks and pump stations. Generally, FD controller are implemented by PIDs or PLC or Fuzzy logic controllers. The next table presents every control system I/O.

Table 17 Company's control systems I/O

Control Units	***Inputs***	***Outputs***
Scheduling of the entire production	Production per factory Order Location of the factory	Segmentation of the production per factory.
Scheduling the production per factory	Daily production Production plant(s) state	Configuration of the production plant(s) Update the server about the production process
Real-time Optimization & fault detection	State signals from field device controllers Signals from field devices (sensors, control valves, tanks, pump stations) Production configurations	State of the production State of the PLs operations Production parameters
Field Device Controller	Signals from the controlled field devices Production parameters	Control signal to the controlled devices State signal of the controlled devices

8.1.2 MPC Application #2

One of the most challenging problems of a soft drink production line is the overflow/underflow effect that is created on every stage of the production which can cause unexpected delays.

Every stage of the production process, from the inspection and cleaning process till the final stage of packaging the bottles, has to manage the bottle flow. This is a rather important task because the controller has to determine the right speed of the conveyor belts, bottling machine, labelling and packaging machines and synchronize all of them. If the speed of one of these machines is slower or faster the result, at that point of the production line, will be the underflow or overflow.

For example, if the conveyor belt provides the bottling machine with more bottles than it can process, so the belt's speed is faster than the bottling machine's speed with the result of overflowing the input area. As a consequence, the bottling machine cannot handle the bottle input and the operators have to stop process and solve the problem. If the speed is slower than the bottling speed then the production line has an underflow problem.

So the production line has to be orchestrated so that every part at any stage of the process is synchronized with each other. MPC can be adopted to determine the optimal speed for every component of the production line.

The MPC receives and handles signals from laser sensors across the entire PL. The laser sensors are used in soft drink PL for scan, level verification as well as for counting the bottles. So the MPC can monitor the speed rate of the bottles in the PL and the speed of the machinery using signals from the FD controllers to regulate the speed of the entire production line. So the MPC synchronizes the PL's machinery.

The MPC approach can be implemented above a DCS, which is handling each component of the plant at the machine level and the MPC is handling the production line.

8.1.3 MPC Application #3

An important task of the production plant is to produce the demanding amount of products with accuracy and repeatability in order to create soft drinks that differ very little from each other. This task has to do with the manufacturing process which consists of the syrup manufacturing, the syrup and water mixing as well as the carbonation of the liquid. According to the order the PL has to produce a certain amount of bottles of the product which means that the production process starts all over again and so the PL has to ensure that the products differs barely from each other. So the control system has to schedule the PL by configuring an optimization & fault detection controller as well as direct control signal to machinery's (FD) controllers. MPC is an appropriate control method which can handle such tasks. The MPC can be implement in a high controlling level such as production scheduling per factory. As it is illustrated in Figure 8.2.

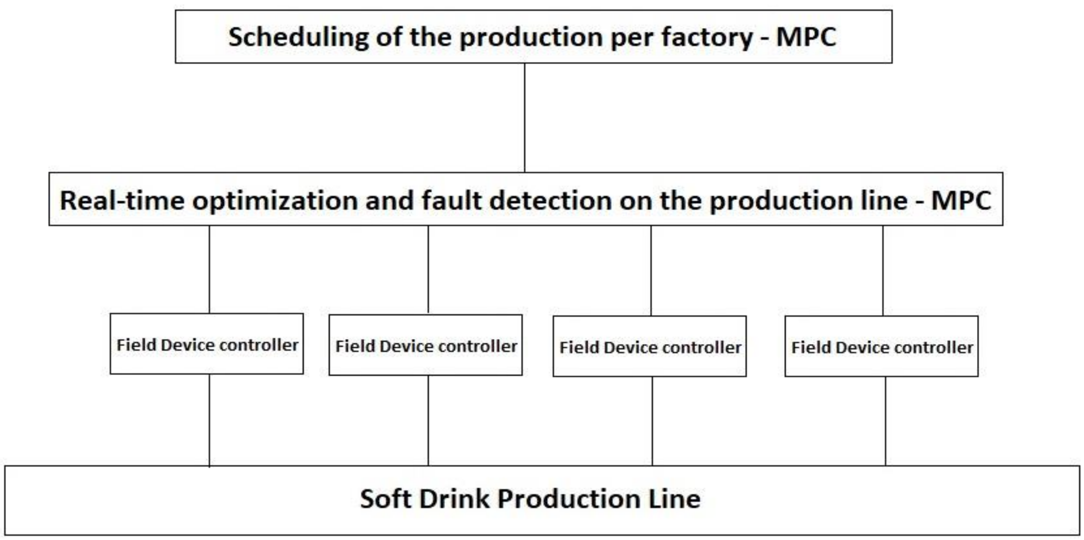


Figure 8.2 Scheduling the factory's production

After the production scheduler there is the core of the PL's control which is the optimization and fault detection unit. This unit is responsible for maintaining the stable operation of the PL and completion of the production. So it is really important for the optimal operation of this control unit to be connected with the entire PL and gather information about its function. So the controller is connected with FD like sensors as well as FD controller such pump station controller. Next, modern PL are using intelligent FD spread across the entire PL which have controllers to manage their operation.

The Table 18 presents the basic I/O of the factory's individual control units.

Table 18 Factory's control system I/O

Controllers	*Inputs*	*Outputs*
Scheduling the factory's production	Product's recipe Daily production Production plant(s) state	Configuration of the production plant(s)
Optimization & fault detection	State signals from field device controllers Signals from field devices (sensors, control valves, tanks, pump stations) Production configurations	State of the production State of the PLs operations Production parameters
Field Device Controller	Signals from the controlled field devices Production parameters	Control signal and state signal to the controlled devices

8.2 Conclusions

In conclusion, in this chapter described three different design approaches of how MPC control can be included in a DCS control system of a soft drink production plant. MPC Application #1 presented an MPC application for the scheduling of the entire company's production process with many factories and different production plants. Next, MPC Application #2 described an MPC application for overflow/underflow control which one of the most challenging problems of a soft drink production line. MPC Application #3 shown an MPC application for the manufacturing process which will has to ensure that the products differs barely from each other.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

Soft drink industry's necessity for evolution due to the fact that the market demands are growing and the products are becoming more and more complex. Even though there are many papers about the performance, factory layout or efficiency of the soft drink production lines there aren't any about the automatic process control of such factories. This research studied the development of a virtual model of a soft drink production line and the design and simulation of a DCS control system focused on a soft drink PL. This concept is tested by simulation results for different operation scenarios, where are situations of normal nominal operation and faulty operation of the PL.

Moreover, for the optimal plant control we designed different approaches where MPC control is incorporated in the DCS.

9.1 Summary

Considering all the above, there is an introduction of the technologies and methods which are developed for automatic process control. CHAPTER 2 has presented the DCS and MPC approaches introducing the reader to the basic theory of these control methods, providing information about the implementation, pros and cons.

Then, CHAPTER 3 presents the selected software tool providing additional information about it. Moreover, this chapter introduces available simulation software tools, open source or commercial (i.e. OpenModelica, EPANET®, LabVIEW®, Dymola® etc.) which can handle complex hydraulic simulations and large scale water distribution network systems.

CHAPTER 4 introduced the field research which had been done and presented different interesting factors of two different production lines. As a result, the data which is collected from the field and literature research combined to synthesize the simplified design of a soft drink PL. The simulation model is explained in the next 2 chapters, CHAPTER 5 and CHAPTER 6 which consists of the production line simulation model and the control system respectively.

CHAPTER 5 presents the virtual structure of the production line model providing the system's block diagrams and virtual design in Simulink, the segmentation of the system into three pipeline sectors, the valves, pumps and sensors specifications as well as the analysis of the individual blocks which were include in the virtual design.

Afterward, CHAPTER 6 presented the control system of the PL, introduced the Distributed intelligence approach which is based on DCS, MAS methods. Moreover, the control system was explained in details presented the control units for every pipeline sectors providing the reader with block diagrams and simulation results.

Then, CHAPTER 7 consists of three simulation scenarios and presented the system's behavior based on different scenarios. Each simulation scenarios lasts **8000** *s* which is more than enough time for the system to finish the production. The first scenario presents the normal, (nominal) operation of the PL, under the condition of stable flow operation of the PL providing stable fluid flow, completing the manufacturing process within **3605.2** *s* or covering the **45.06%** of the simulation time and the bottling process **3652.4** *s* or **45.7%** of the simulation time. As a result, design DCS manages to bottle $\mathbf{6*10^3}$ *lt per hour*. The second scenarios shows that the designed DCS manages an unexpected flow drop caused by a pump malfunction, stabilizes the water pipeline's flow in **70** *s* or **0.87%** and finishes the manufacturing process in **3608.4** *s* or **45.1%** of the simulation time. As a result, the time difference in manufacturing process between the two simulating scenarios is almost **0.04%** of the simulation time or **3.2** *s*. The production operation of the soft drink PL terminates after bottling $\mathbf{6*10^3}$ *lt per hour*. The last scenario demonstrates two pumps malfunctioning. The control system manages the first malfunction by regulating the remaining pumps and stabilize the flow at the operating range (like in Scenario #2: Malfunction of one of the three pumps). The system was stabilized and operational for **1197** *s* but when the second malfunction occurred, the control system evaluate the performance of the system and terminates the operation of the PL after the **3199** *s* of the simulation, covering the **40%** for the simulation time, following the safety protocols.

The CHAPTER 8 introduced three MPC approaches which can be applied in different control levels of a soft drink production line. First application described how an MPC control can be included for scheduling of big scale companies production process with many factories and different production plants. The next application presented an MPC application for overflow/underflow control which one of the most challenging problems of a soft drink production line. The last application shown how an MPC control could be implemented into the manufacturing process, ensuring that the products differs barely from each other (quality control).

9.2 Concluding statements

9.2.1 Personal Statement

The research's goal was to study a very rapidly evolving industry, the soft drink industry, and the development of automatic process control. As far as I am concerned, automatic process control and control engineering are crucial parts of the production process and as the industries are moving towards the IoT such technologies will be developed even more.

During my study I was motivated by the fact that the literature about the automatic control of soft drink production lines was very poor. This thesis provided me with the opportunity to present the reader a different scope of production control processing focusing on the flexibility and reconfigurability of the PL.

Furthermore, I had to study control methods which I hadn't experienced before and imbedded them to a real-life production line applications. Thus, I had the fortune to tour in two soft drink factories, study their PL and discuss with the chief-engineers about the performance, production process, possible problems and difficulties and overall about the operation of a bottling factory. Based on that, I had to study dynamic simulation to design a simplified, virtual model of a PL consisting of numerus hydraulic and electronic blocks using Simulink and MATLAB® as well as research for additional software tools more suitable for dynamic simulation.

9.2.2 *Limitations of the work*

An important task of this research is to gather and present information about the available, commercial or not, software tools. This was really difficult due to the fact that the best software tools are commercial available which was a limitation. Obviously, all of companies were offering a trial or a demo edition of their software which I requested and I had to wait many months for the companies to answer my applications and in many cases to reject them. As a result, I chose to present some of the software available in the market and include basic information instead of writing a brief review.

Completing the model of the system I designed a dashboard, an operating interface (HMI), which was responsible to inform the operator about the tanks capacity level, flow rate, pressure rate and speed diagrams as well as to offer manual operation if it is needed. Unfortunately, due to my PC's weak CPU/GPU power and RAM capacity I couldn't run and further develop more graphically demanding designs. The generic idea is illustrated in **Error! Reference source not found.**.

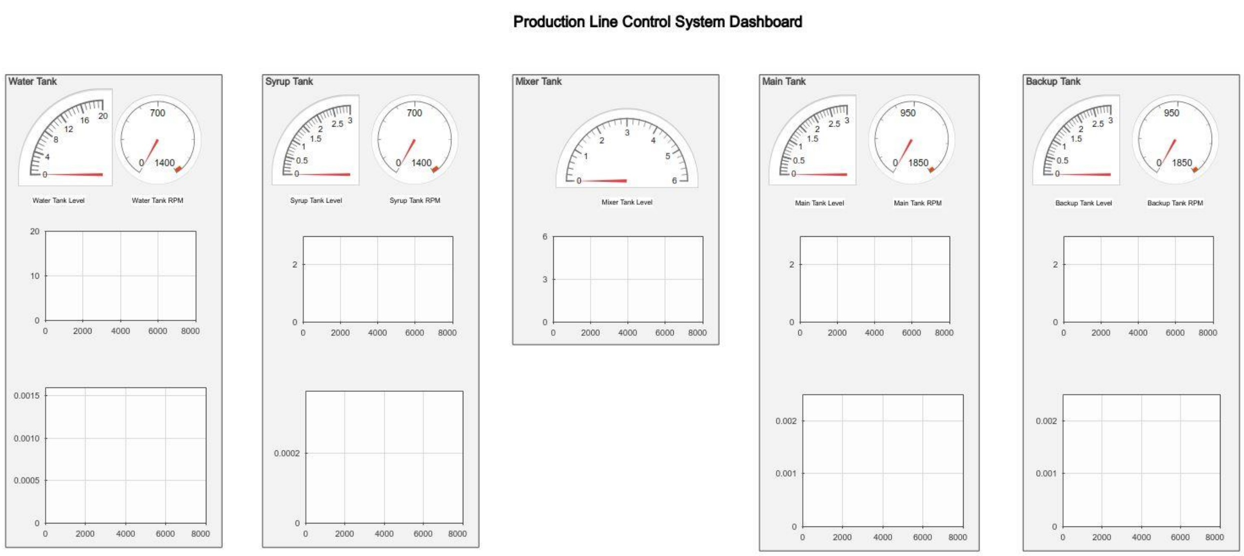


Figure 9.1 Production line control system dashboard

9.3 Recommendations and Predictions

The scope of the thesis was just the tip of the iceberg. This thesis could be the starting point for many different projects based on the idea for further development and evolution of the soft drink industry. As it was presented there is a lot of potential on field of automatic process control with the use of MPC, DCS and MAS or a hybrid combination between them or other methods (see subchapter 6.1).

Another interested project would be the further improvement of the dynamic simulation model introducing more complex production line models and more sophisticated control units as well as developing controller on different manufacturing division (like illustrated in Figure 2.1).

Furthermore, there is a lack of paper or review researches which will test the available software tools based on performance, usability, results, designing methods etc. To my mind, this kind of research is really essential because it offers useful information to future users about the available tools as well as provides a really good feedback to the developer for further adjustments and development.

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