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A SUPERVISORY CONTROL SYSTEM FOR AUTOMATION OF HORIZONTAL FORM-FILL-SEAL PACKAGING PLANT BASED ON MODIFIED ATMOSPHERE TECHNOLOGY

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Abstract: The packaging industry is one of the most important parts of agricultural products processing. A popular method of increasing the shelf life of agricultural products is modified atmosphere packaging (MAP). The main objective of this paper was to increase the adaptability and flexibility of the machines for packaging of different vegetables including lettuces, broccolis, cabbages, cauliflowers, etc. To achieve this goal, a supervisory control and data acquisition (SCADA)-based system was designed and developed for controlling and monitoring of MAP process of fresh vegetables. The system was divided into three physical layers: field devices, remote terminal unit (RTU) and master terminal unit (MTU). For packaging width adjuster system, the R^2, maximum error (ME), mean absolute error (MAE) and root mean square error (RMSE) were obtained as 0.999, 8 mm, 2.96 mm and 3.44 mm, respectively. For packaging height adjuster system, the R2, ME, MAE and RMSE were obtained as 0.994, 10 mm, 3.53 mm and 4.57 mm, respectively. The SCADA system can be able to accurately adjust the speed of the conveyor and the temperature of the sealing jaws, based on the desired values. For gas injection unit, the value of 1.66 L/min, 0.557 L/min and 0.667 L/min were recorded for ME, MAE and RMSE, respectively. Four types of trends including temperature, speed, flow and digital parameter trends were designed. In addition to displaying screen alarms, the occurred alarms are stored, automatically as a text file for troubleshooting. Finally, the results showed that the designed system can be reliably used for MAP of various varieties of fresh vegetables.

Key words: packaging, food industry, SCADA systems

1. INTRODUCTION

Packaging engineering is a profitable, important and substantial part of agricultural and food products processing. Packaging of fresh vegetables and fruits is more significant. After harvesting and due to breathing and also dealing with environmental air, a series of chemical reactions occur in the produce, and thus, the moisture is lost. Therefore, wrinkles, discolouration, dehydration, changes in texture and freshness loss or corruption occur in the products. A popular method of increasing the shelf life of agricultural produces is to use modified atmosphere packaging (MAP). In this technique, the headspace of the package is replaced with a specific pure gas or a mixture of several gases such as oxygen (O_2), nitrogen (N_2) and carbon dioxide (CO_2) with a certain proportion. The mixture of gases and the ratio of each gas in the mixture are important and are chosen as a function of the product that is packaged by the modified atmosphere technique. In order to eliminate hygienic problems related to human health and minimise human intervention, the packaging process requires adequate control and a high level of automation of fresh vegetable packaging plants, to improve the quality of products and efficiency of the system. In order to automate the plant, there is a need to develop a system that monitors the plant and helps reduce the errors caused by humans.

Nowadays, more and more complex, safe and trustworthy automation and control systems are required to support the technological change towards the factories of the future concept. This means that automation and control systems must automate, control and optimise the production processes ensuring plant availability while providing high-quality production with zero defects [1]. In particular, the automation system should facilitate a great deal of online modification including I/O interfacings, instrumentation hardware, diagnostics, prognostics, and data collection and operator interfaces [2].The processing and packaging control system of agricultural products (especially fresh fruits and vegetables) embeds a generic set of essential requirements with regard to timing, error diagnostics, coordination and synchronisation. Moreover, the imperative error recovery and fault corrections are needed during run time. Furthermore, the control systems should satisfy other fault-tolerant features such as interlock checking and intuitive status display with error messaging [3].

Several controlling methods of agricultural crops processing especially in the field of packaging have been utilised. One of the most proper automation technology seems to be supervisory control and data acquisition (SCADA). This technology has been widely applied in the recent decade in the food industry [4].

The SCADA system has been extensively used in the food industry. Kumar and Rani [5] proposed an automation system using SCADA for the preparation, bottling and packaging of soft drinks.

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Kulkarni and Elango [6] developed an automatic filling system by SCADA. They reported that the controlling and monitoring process by SCADA reduced errors in the system. Singh et al. [7] presented a method aimed towards providing a smart automation system in sugar mill. The graphical programming software LabVIEW has been utilised to develop SCADA software. By using a smart SCADA system, the performance and reliability of the sugar mill have been improved [7]. Lima et al. [8] developed a remote monitoring system based on the SCADA model in the field of food industry. They used the SCADA system for monitoring of production rate, packed quantity and Overall Equipment Effectiveness (OEE). The system also included alarms management, process trending and data logging [8]. The paper of Jain et al. [9] proposed a SCADA simulation model for packaging system in dry ice plant to improve packaging and extensively reduce operating labour costs. Sinha et al. [10] focused on a real-time flow measurement system using the Hall probe sensor and personal computer (PC)-based SCADA. In the paper, a float carrying a thin circular permanent magnet was used and a Hall probe sensor was placed outside the rotameter tube to sense the variation of magnetic field of a magnet with variation of float position. The DC signal output of the measuring system has been sent to a PC-based flow indicator. The flow indicator has been designed using Lab Tech Note Book Pro software and PC-based SCADA system. The performance of the system has been tested experimentally. A very good repeatability and a linearity of results have been reported [10]. Also, an oxygen control system was designed and developed by Catania et al. [11] for malaxation machine to improve virgin olive oil quality. The developed system is composed of an oxygen concentration sensor directly connected to the malaxation chamber and a data acquisition system to analyse and store the measured values in a process database [11]. The automation of systems in other aspects of manufacturing systems related to agriculture has been investigated by researchers. The paper of Szymenderski and Typańska [12] presented a model of controlling the flow of energy in agricultural biogas plant. The biogas plant control algorithm has been modelled using SCADA software, and an analysis of cost performance and life of the investment have been performed [12]. Aziz et al. [13] proposed a SCADA system to monitor and predict changes of humidity and temperature level in the greenhouse atmosphere. The system included active measurements, which were capable of detecting degradation level for humidity and temperature, were equipped with an alert mechanism to notify workers about the atmosphere quality in the greenhouse [13]. The paper of Bhutada et al. [14] discussed the automation of a free-standing greenhouse using SCADA system. The system was designed to achieve the optimal level of environment and growth factors inside the greenhouse and also present an efficient and user-friendly way of greenhouse automation [14].

In the field of fruit and vegetables, SCADA-based systems were scarcely implemented. Fresh vegetable packaging machinery usually does not have an advanced control system, while many packaging parameters are manually adjusted which necessitates the presence of the operator. However, the modern multi-target concept of fruit and vegetables packaging machinery is more attractive with recent technologies to develop the packaging systems having the ability to pack different agricultural products with different sizes, modified atmosphere conditions and packaging materials. Nevertheless, some researchers have focused on applying SCADA in preserving fruit and vegetables during storage. Ramesh Babu et al. [15] studied on applying SCADA systems in the automation of controlled atmosphere stores and suggested suitable systems for automatic control and remote monitoring of all the parameters for a better shelf life of fruit and vegetables. Yu et al. [16] developed a remote SCADA system for keeping fruits and vegetables fresh. The system was divided into three physical layers: the field control unit at the bottom, a host computer control system in the middle and the remote monitoring layers at the top [16].

In order to preserve the quality of fresh vegetables using the MAP technique, different parameters such as flow rate and ratio of injecting gases, sealing temperature and packaging speed should be accurately controlled and then many true decisions should be made. Also, manufacturing processes in the agricultural industry are usually hard to be automated due to their non-uniformity, high variability of raw materials and also due to the scarcity of sensors for real-time monitoring of the key variables. To the best of our knowledge, there is no effort given to the automation of the whole process of fresh vegetable packaging systems, and many affecting parameters are manually changed by operators such as packaging width and height. Also, the present systems do have not an appropriate compatibility to use for packaging of different types of fresh vegetables.

Although Programmable Logic Controller (PLC)-based architecture is commonly used in packaging machinery, they are not developed for making data records, connecting to a central control system, alarms, etc., whereas the implementation of advanced automation and control strategy in the vegetable packaging domain plays a vital role. In comparison with the traditional methods, advanced control systems have several advantages. The traditional methods use discrete electronics, PLCs, Industrial computers and even high-computing systems such as the Digital Signal Processor (DSP) platform. These automation platforms have issues such as reliability, flexibility and scalability [17]. In a competitive and constantly changing environment, it is critical to identify and select the most current and appropriate technology that will satisfy the new need at the least cost. In the packaging of vegetables, the key aspects that should be considered are the product characteristics, packaging requirements and production facilities [18].

Motivated by the shortcomings in the current state-of-the-art, and to increase the adaptability and flexibility of the machines for packaging of different vegetables including lettuces, broccolis, cabbages, cauliflowers, Brussels sprouts, etc., this paper establishes research on automation of these systems based on supervisory control technology.

The most innovative aspect is the transition from an old rigid concept to a conception with distributed unit operation-based systems in a packaging factory controlled by a central unit. This allowed great freedom of action in packaging different types of vegetables with different shapes, dimensions and sizes. Therefore, flexibility is an important factor that makes it possible to change the packaged good characteristic, weight, size, wrapping materials, etc. [19]. The majority of vegetable packaging machine factories build their product in small batches or in individual operating modes which makes it necessary to supervise a human operator on each unit machine.

Based on the aims of this paper, a SCADA-based system was designed and developed for controlling and monitoring of packaging process of fresh vegetables using modified atmosphere technology. The designed SCADA system was implemented on the fabricated Horizontal Form-Fill-Seal (HFFS) plant. It allows to visualise the entire system and inspect of individual influencing factors so that it is possible to continuously and precisely control the process. The possibility of recording data is another advantage which allows us for subsequent analysis in order to evaluate the correctness of the system. Computer, controllers, instruments, actuators and interfaces provide supervisory control of the automated process and allow analysis of the system through data acquisition.

2. MATERIALS AND METHODS

2.1. Experimental HFFS plant

A HFFS plant was designed and fabricated for packaging of fresh vegetables such as lettuce and cabbage. Fig. 1 shows the fabricated packaging plant.

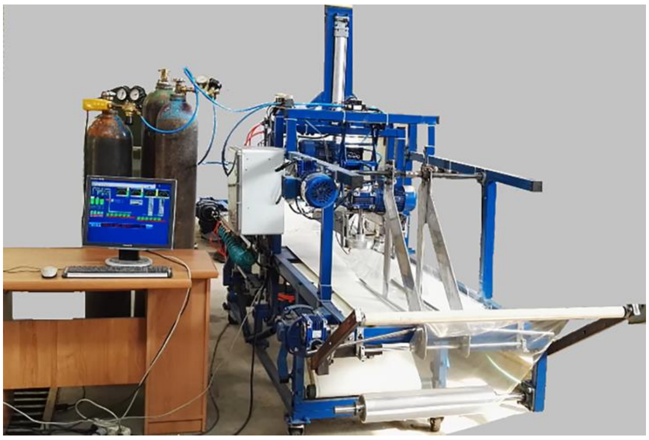

Fig. 1. The fabricated HFFS plant for MA packaging of fresh vegetables. HFFS, horizontal form-fill-seal

The packaging process of the HFFS plant includes the following tasks. First, fresh wholesome and cleaned vegetables are put on the conveyor, consecutively and in a line. At the entrance of the machine, a polymeric film is pulled and stretched on the conveyor and beneath the fresh products. The polymeric film passes through a forming collar, named the folding box, and then is transformed into a tube and after that, the two edges of the polymer are sealed together by the heated wheel sealers under a definite pressure and temperature. Gas flushing is used for atmosphere modification by a lance that is entered into the tube when the HFFS plant is operated [20]. The gas mixture used for modification of the packaging headspace usually includes O_2, CO_2 and N_2. The box motion cross-sealing unit is designed to extend the dwelling time by which the cross-sealing jaws that are in contact with the polymeric film. So it can be able to transfer more heat and long-time press into the film as opposed to increasing temperature which can potentially melt the film. To make a box motion unit, separate pneumatic actuators were used for the horizontal and vertical motions allowing a variable amount of jaw separation and dwell distance to be achieved. A knife, integral with the sealing jaws, cuts through adjacent packs to produce the separation. Fig. 2 illustrates the components of the fabricated HHFS plant.

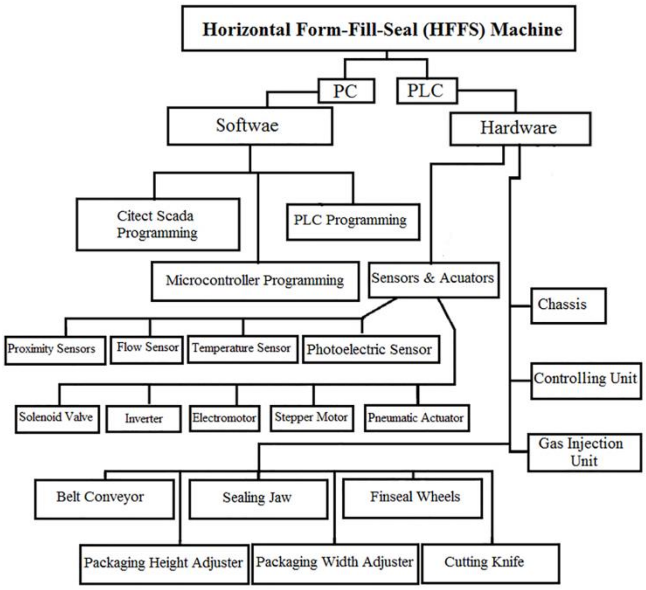

Fig. 2. The components of the fabricated HFFS plant. HFFS, horizontal form-fill-seal

2.2. SCADA system structure

The developed SCADA system is illustrated in Figs. 3 and 4. The system as a whole is divided into three physical layers: field devices at the bottom including instruments, sensors and actuators being responsible for the acquisition of input signals and delivery of control ones to the processes [21]; remote terminal unit (RTU) including a PLC; the supervision control layer is implemented by the Master Terminal Unit (MTU), typically a computer (e.g. a personal computer), that periodically collects data from the process control layer. The MTU ensures essential functionalities such as alarms management, data logging, processes trending and reports generation [8].

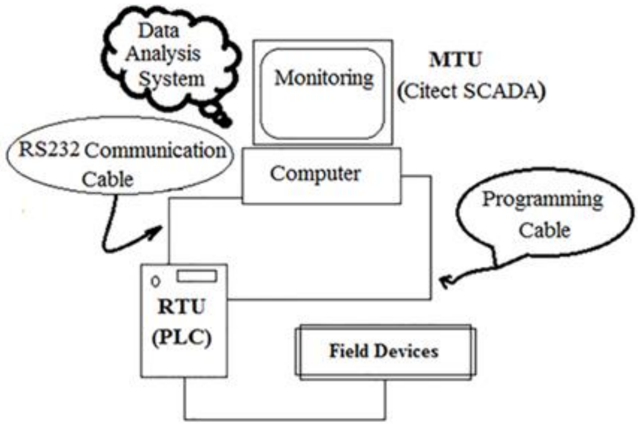

Fig. 3. The developed SCADA system architecture for the HFFS Machine. HFFS, horizontal form-fill-seal; SCADA, supervisory control and data acquisition

The applied sensors for measuring the physical parameters in the controlling system of the HFFS plant are composed of temperature sensor for sealing jaws, infrared distance measuring sensor for packaging width and height adjuster units, magnetic position detector for pneumatic cylinders, inductive proximity sensor for speed measurement of the conveyors and fin-wheel sealing jaw and photoelectric sensor for vegetable passing detection and digital gas flow sensor for gas injection treatment.

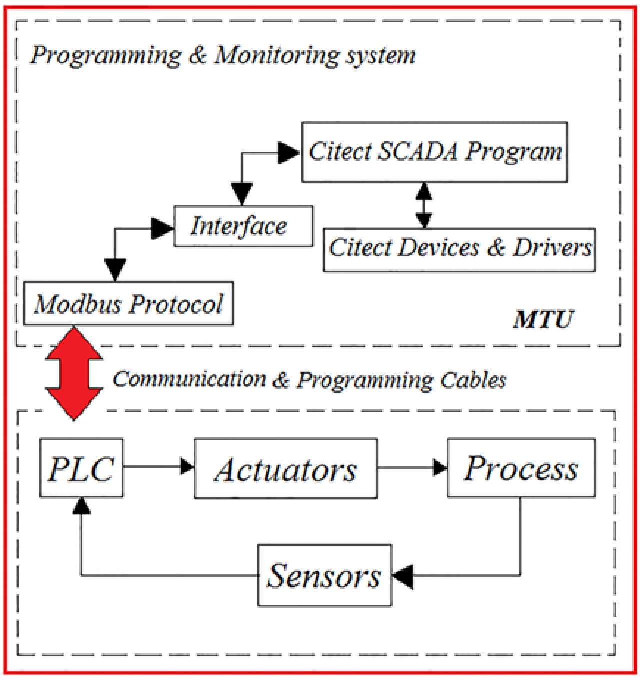

Fig. 4. Diagram of monitoring and controlling system

Two precision centigrade temperature sensors (LM35) were used for measuring the temperature of the cross-sealing and fin-wheel sealing jaws. The output voltage of the sensor is proportional to the sensed temperature with sensitivity of 10 mV/°C. To install the sensors, a hole with diameter and depth of 6 mm was drilled on the cross-sealing and fin-wheel sealing jaws, and then the sensors were fixed into the holes.

To measure the packaging width and height, two infrared distance measuring sensors (Model: GP2Y0A21YK0F, SHARP) were installed on the chassis of the HFFS plant. The output voltage of the sensor is corresponding to the detection distance, but there is a nonlinear relationship between the output voltage and the detected distance, so a pre-experiment was performed for extraction of the best calibration equations.

A magnetic sensor was applied for position detection of the pneumatic actuators that should be installed on the cylinders. For each actuator, two sensors were used to recognise if the actuator is in the open mode or closed one.

For conveyor and wheel seal speed measurement, the inductive proximity sensors (FOTEK, PM-18-08) were used as a rotational speed counter (rpm). By multiplying the diameter of the roller and the rotational speed, the linear speed of the roller or wheel would be calculated.

The photoelectric sensor (OMRON, E3JK) was used for vegetable passing detection through the vertical sealing jaws. When the sensor detected the vegetable, a positive pulse is sent to the PLC and the end seal of the package is performed by sealing jaws.

Three gas flow sensors (Honeywell Zephyr, HA-FUHT00300L4AXT) were used for measuring the flow rates of N_2, O_2 and CO_2 gases through atmosphere modification. The sensors provide Inter-Integrated Circuit (I^2C) protocol for reading gas flow over specified full-scale flow and compensated temperature ranges. So, a digital interface was designed for the sensors. The interface receives the output of the gas flow sensor and then converts it to analogue voltage. Also, the PLC receives the analogue voltage and converts it to digital form again. Fig. 5 shows the designed interface for the gas flow sensors. The gas flow rate is calculated as follows:

$$F = 300 \times \frac{\left[\frac{DOC}{16384} - 0.1\right]}{0.8} \quad (1)$$

where F is the gas flow (L/min) and DOC is the digital output code of the sensor.

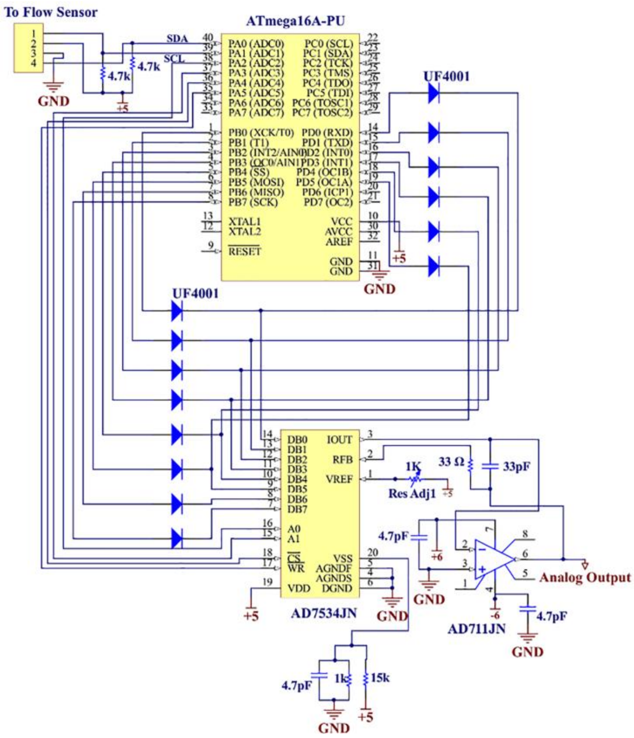

Fig. 5. The electronic circuit diagram of the designed digital interface for communication between the gas flow sensor and PLC. PLC, programmable logic controller

The duty of the actuators is to receive commands from RTU and carry out relevant operations. RTU by analysing the received data from the sensors sends specified commands to the actuators and decides for the next step after the reception of appropriate feedback. The actuators of the HFFS plant are LS IG5A frequency inverter, pneumatic solenoid valves, flow control valves for injecting gases, relays for turning on or off the electromotors and heating elements of sealing jaws. Two IG5A inverters were used for controlling the speed of the conveyors and wheel seal jaw.

The control unit of IG5A has analogue and digital inputs, so that it can take commands from PLC to turn on and off the electromotor and adjust the speed of the motors, also provides forward and reverse turns to change the rotating direction of the motors. Three 5/2-way single solenoid valve spring return were used for controlling the pneumatic cylinders of the upper and bottom vertical sealing jaws and cutting knife. Also, to control the pneumatic cylinder of the carrier of the vertical jaws, a 5/3-way double solenoid valve closed mid-position was used. Three automatic flow control valves were fabricated using a manual flow control valve, stepper motor and driving system for adjusting the ratio of injecting gas mixture. An electronic driver module was designed as a control unit of flow valves to receive command signals from the PLC. The N_2, O_2 and CO_2 gases are usually used for headspace modification in packaging engineering. Fig. 6 shows the fabricated automatic flow control valves and the driving module.

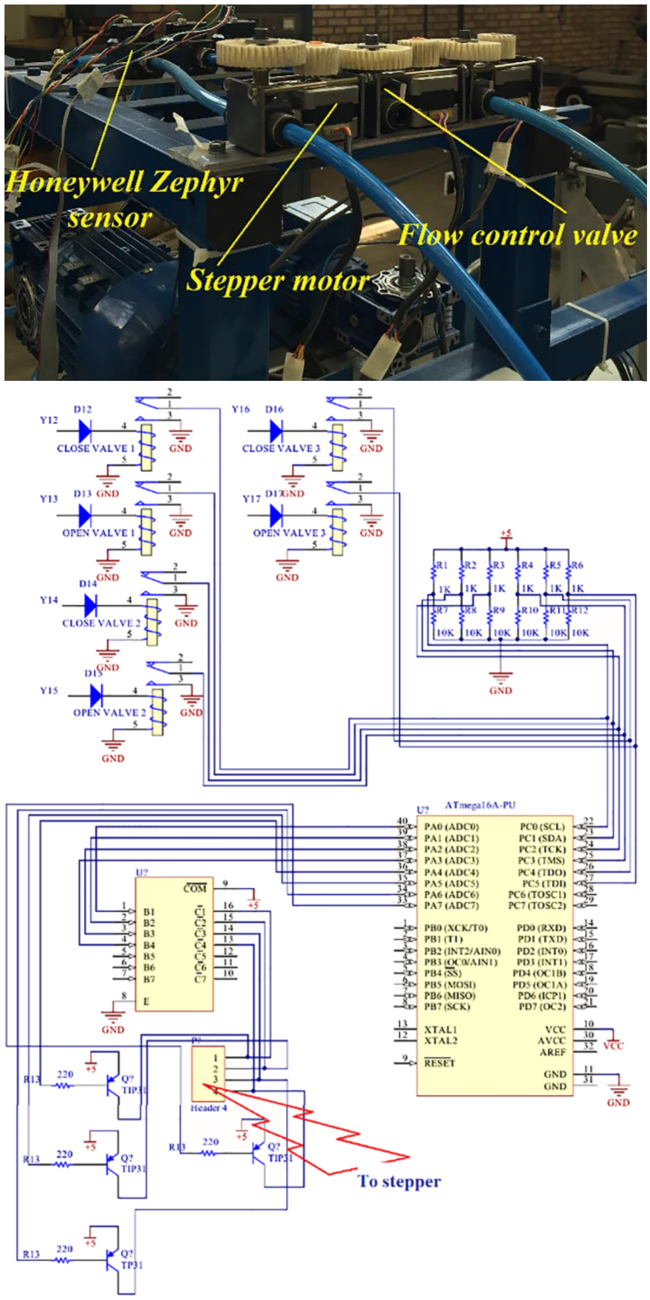

Fig. 6. The injection system for N2, O2 and CO2 gases

According to Tab. 1, the total number of input and output digital parameters and input and output analogue parameters are 8, 20, 7 and 2, respectively. So, a PLC with 20 digital inputs and 12 digital outputs (Model: FBs-32MBR2-AC, FATEK) was used as RTU. Also, a digital output module (FBs-8Y), an analogue input module (FBs-6AD), an analogue output module (FBs-2DA) and a serial communication board (FBs-CB2) were used for extension of the selected PLC.

Tab. 1. Identification of input and output parameters of PLC

Device	Type	Supply voltage (V)	Output voltage (V)	No.
Temperature sensor	Analogue input	5	0–1.55	2
Distance measuring sensor	Analogue input	5	0–3.5	2
Flow rate sensor	Analogue input	5	0–5	3
Photoelectric sensor	Digital input	24	24	1
Inductive proximity sensor	Digital input	24	24	3
Magnetic sensor	Digital input	24	24	4
Inverter speed adjuster	Analogue output	0–10	–	2
Solenoid valve	Digital output	24	–	5
Flow control valve	Digital output	24	–	6
Gas injection valve	Digital output	24	–	1
Relay for electromotor	Digital output	24	–	3
Relay for heat element	Digital output	24	–	2
Starter relay for inverter	Digital output	24	–	3

PLC, programmable logic controller

The developed RTU supports the industrial ModBus RTU protocol. So, the used devices for communicating the RTU and MTU are ModBus/RTU protocol, RS232 interface, communication cable and communication board (FBs-CB2, which was installed on the RTU). The ModBus protocol is widely used in the agricultural industry and was developed in 1979 by Modicon Inc. ModBus communicates using a master–slave technique as a messaging structure, and so does not define a physical layer. Normally, the RS232, RS422 or RS485 protocols are used as the physical layer. ModBus allows flexible access to the measured values and configuring parameters of the intelligent devices. Depending on the complexity of the processing flow, different devices can be connected to the network [22, 23].

The supervision control layer is implemented by MTU, typically a computer (e.g. a personal computer) and SCADA-based software. The master computer performs two-way data exchange with the slave computer (PLC) using ModBus protocol. The supervisory computer system periodically collects the data from the process control layer. The system software used in this research is CitectSCADA-7.1 (Schneider Electric).The software consists of two distinctive parts: configuration environment and runtime. The configuration environment includes tools for making runtime, designing and managing of the supervisory system. The runtime environment is a graphical interface that communicates with the I/O devices so the administrator can perform the supervisory control and manages the overall system. To develop the SCADA system, in the first phase, a new project was created in Citect Explore. The next steps are defining labels for control variables, communication settings, server settings, system settings, alarms, monitor screen design and programming in Cicode Editor.

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The variable database is the most essential part of the SCADA system that has different formats such as digital, integer and real. Tab. 2 shows the defined variables in the developed SCADA system.

Tab. 2. Defined variables in CITECT SCADA and memory of the PLC

Tag name	Type	Unit	Tag name	Type	Unit
Conveyor 1 Speed Sensor	DIGITAL	None	Reverse Run M2 M3 M4	DIGITAL	None
Wheel Seal Speed Sensor	DIGITAL	None	Gas Injection Valve	DIGITAL	None
Product Passing Detector	DIGITAL	None	Actual Value Wheel Seal Temperature	REAL	°C
Conveyor 2 Speed Sensor	DIGITAL	None	Actual Value Sealing Jaw Temperature	REAL	°C
Position Detector Cutting Knife	DIGITAL	None	Operator Input Wheel Seal Temperature	INT	°C
Position Detector Vertical Actuator	DIGITAL	None	Operator Input Sealing Jaw Temperature	INT	°C
Closing Detector Horizontal Actuator	DIGITAL	None	Actual Value Packaging Width	INT	0.1 V
Opening Detector Horizontal Actuator	DIGITAL	None	Operator Input Packaging Width	INT	mm
Product Passing Detector	DIGITAL	None	Actual Value Packaging Height	INT	0.1 V
Up Vertical Actuator	DIGITAL	None	Operator Input Packaging Height	INT	mm
Cutting Knife Actuator	DIGITAL	None	Reference Conveyor Speed	INT	m/s
Down Vertical Actuator	DIGITAL	None	Actual Value Conveyor Speed M1	REAL	m/s
Opening Horizontal Actuator	DIGITAL	None	Actual Value Conveyor Speed M5	REAL	m/s
Closing Horizontal Actuator	DIGITAL	None	Actual Value Wheel Seal Speed M3	REAL	m/s
Packaging Width M2	DIGITAL	None	Dueling Time	INT	10 ms
Wheel Seal M3	DIGITAL	None	Gas Flow Sensor 1	REAL	SLPM
Packaging Height M4	DIGITAL	None	Gas Flow Sensor 2	REAL	SLPM
Heat Element Sealing Jaw	DIGITAL	None	Gas Flow Sensor 3	REAL	SLPM
Heat Element Wheel Seal	DIGITAL	None	Carrier Opening Speed	REAL	m/s
Forward Run Conveyor M1 & M2	DIGITAL	None	Carrier Closing Speed	REAL	m/s
Forward Run M2 M3 M4	DIGITAL	None	Gas Flow Sensor 1	REAL	SLPM
Close Flow Valve 1	DIGITAL	None	Gas Flow Sensor 2	REAL	SLPM
Open Flow Valve 1	DIGITAL	None	Gas Flow Sensor 3	REAL	SLPM
Close Flow Valve 2	DIGITAL	None	Heat Element Control	DIGITAL	None
Open Flow Valve 2	DIGITAL	None	O_2 Flow Control	DIGITAL	None
Close Flow Valve 3	DIGITAL	None	CO_2 Flow Control	DIGITAL	None
Open Flow Valve 3	DIGITAL	None	N_2 Flow Control	DIGITAL	None

PLC, programmable logic controller,
SCADA, supervisory control and data acquisition

The communication settings connecting the master computer and the slave PLC are shown in Tab. 3. Citect acquires the data sent by the slave computer and displays some needed data on the monitor display. Moreover, operator may manually transmit commands to the PLC through the RS232 port.

Tab. 3. Communication settings of MTU and RTU

Parameter	MTU	RTU
Protocol	ModBus/RTU	ModBus RTU (Slave)
Baud rate	115,200	115,200
Stop bit	1	1bit
Data bit	8bits	8bits
Parity	EVEN-P	Even parity

MTU, master terminal unit; RTU, remote terminal unit

The functionality of alarms is to declare abnormality occurrence in the system, warning to operator if the current situation causes damage to the machine, defective product or imperfect process. For instance, if the temperature of the sealing jaws would be lower than the adjusted value, the packaging process would not be completely implemented and faulty sealing edges would be produced. The defined alarms are categorised into three groups: digital, analogue and advanced. The defined alarms are presented in Tabs. 4–6.

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Tab. 4. Communication settings of MTU and RTU

Alarm tag	Alarm description
Conveyor_Motor	Conveyor Motor STOPPED
Gas_Injection	Gas Valve Injection CLOSED
Jaw_Element	Jaw Element Seal Turned OFF
Wheel_Element	Wheel Seal Element Turned OFF
Wheel_Motor	Wheel Seal Motor STOPPED

MTU, master terminal unit; RTU, remote terminal unit.

Tab. 5. The analogue alarms defined in Citect

Alarm tag	High–high	High	Low	Low–low	Deviation
Seal temperature	140	135	100	95	5
Wheel temperature	180	160	125	120	5
Conveyor speed	0.2	0.18	0.08	0.06	0.01

Tab. 6. The advanced alarms for HFFS

Alarm tag	Alarm description	Cicode expression
OverFlow1	O_2 Flow>=300	GAS_FLOW_OXYGEN>=300
OverFlow2	N_2 Flow>=300	GAS_FLOW_NITOGEN>=300
OverFlow3	CO_2 Flow>=300	GAS_FLOW_CO₂>=300

HFFS, horizontal form-fill-seal

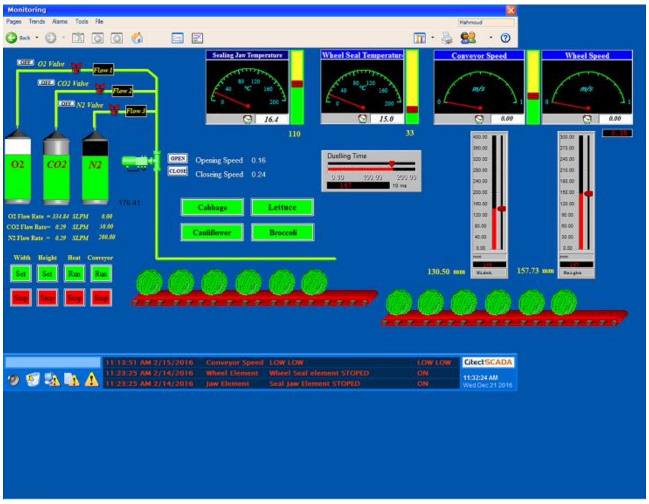

Fig. 7. The graphic page designed for the HFFS system.
HFFS, horizontal form-fill-seal

The graphic page establishes a visual communication between the user and the SCADA system. On the graphic page, objects and buttons trigger a process or do an action. The parameters that should be assignable for the user are temperature of sealing jaws, speed of conveyor and fin-wheel sealing jaws, width and height of packaging, duelling time, injecting gas flow rate, gas injection valve and conveyor status (ON or OFF) and type of the product (lettuce, cabbage, etc.). All these parameters are configurable and operator can be able to change their values. The triggered alarms are displayed at the bottom of the screen. Citect audio features also were used to notify the user the occurrence of alarms. Fig. 7 illustrates the graphic page designed for the packaging system.

2.3. MAP conditions of fresh vegetables

The composition of the required gas in the MAP approach depends on the type of the product, its moisture content, microbiological specifications, breathing rate, the preservation of its colour and the storage temperature. Tab. 7 shows the optimum value of components in the modified atmosphere. The required value of each component was saved in the SCADA system and determined regarding the target product.

Tab.7. Required gas portion for different horticultural products [24]

Horticultural products	Temperature (°C)	Oxygen (%)	Carbon dioxide (%)	Nitrogen (%)
Artichokes	0–5	2–3	2–3	94–96
Asparagus	0–5	15–20	5–10	70–80
Beans	5–10	2–3	4–7	90–94
Beets	0–5	2–5	2–5	90–96
Broccoli	0–3	1–2	5–10	88–94
Brussels sprouts	0–5	1–2	5–7	91–94
Cabbage	0–5	2–3	3–7	90–95
Cantaloupes	3–7	3–5	10–15	80–87
Carrots	0–5	3–5	2–5	90–95
Cauliflower	0–2	2–3	2–5	92–96
Celery	0–5	1–1	0–5	94–99
Corn, sweet	0–5	2–4	5–10	86–93
Cucumbers	8–12	3–5	0–2	93–97
Honeydews	10–12	3–5	0–2	93–97
Leeks	0–5	1–2	3–5	93–96
Lettuce	0–5	1–3	0–3	94–99
Mushroom	0–3	Air	10–15	Air
Okra	8–12	3–5	0–2	93–97
Onions, dry	0–5	1–2	0–5	93–99
Onions, green	0–5	1–2	10–20	78–89
Peppers, bell	8–12	3–5	0–2	93–97
Peppers, chilli	8–12	3–5	0–3	92–97
Potatoes	4–10	2–3	2–5	92–96
Radish	0–5	1–5	2–3	92–97
Spinach	0–5	18–21	10–20	72–59
Tomato	15–20	3–5	0–3	92–97

3. RESULTS AND DISCUSSION

3.1. Calibration of distance sensor

For the infrared distance measuring sensors, there is a linear relationship between output voltage and inverse value of the sensed distance. However, the following hyperbolic model was developed to extract an accurate calibration equation for the distance sensors:

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$$D = \frac{aV+b}{cV+d} \quad (2)$$

where D is the sensed distance (cm), V is the output voltage of the sensor (0.1×V) and a,b,c,d are the calibration equation constants.

The Levenberg–Marquardt method of curve fitting and cftool of MATLAB R2013a was used to extract the calibration constants; the initial value of constants (a, b, c and d) was assumed equal to 1. The Levenberg–Marquardt method has been widely used in many fields due to its high converging efficiency to obtain the global optimal solution. This method takes advantage of the steepest descent method, the Newton method and the Gauss–Newton method. The steepest descent method obtains the local optimal solution with the first-order convergence and has no limitation on the initial values of parameters [25]. The obtained results are presented in Tab. 8.

Tab. 8. The obtained regression coefficients for infrared distance measuring sensor

Parameter	a	b	C	d	R^2	RMSE
Packaging width	0.0662	–5.749	9.5×10^{-5}	0.0016	0.9998	2.102
Packaging height	–0.0117	1.918	5.06×10^{-5}	0.00035	0.9973	3.771

RMSE, root mean square error

The maximum error (ME) of packaging width and height measurements were obtained as 3.5mm and 5.2mm, respectively. Evaluation of the SCADA system is presented as follows.

3.2. Packaging width and height system

The packaging width and height adjuster units were designed so that to be adjustable in the range of 130–400 mm and 150–300 mm, respectively. To evaluate this section of the system, the reference values of width and height of packaging were changed in the monitoring system with interval of 10mm, and the corresponding actual value of these variables was measured using a vernier calliper with an accuracy of 0.1 mm. Fig. 8 shows the reference and actual values of the packaging width.

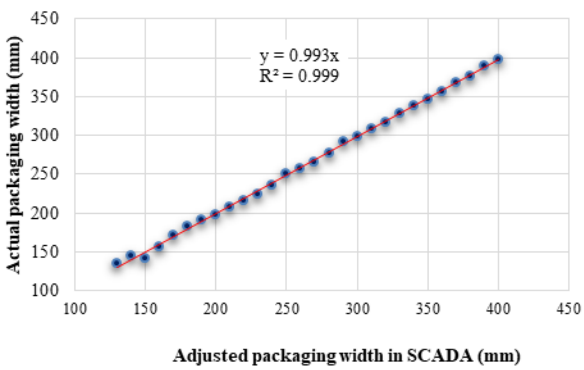

Fig. 8. Fitness of the adjusted and the measured values of packaging width

The R^2, ME, mean absolute error (MAE) and root mean square error (RMSE) were obtained as 0.999, 8 mm, 2.96 mm and 3.44 mm, respectively. Fig. 9 shows the adjusted value of packaging height versus measured ones.

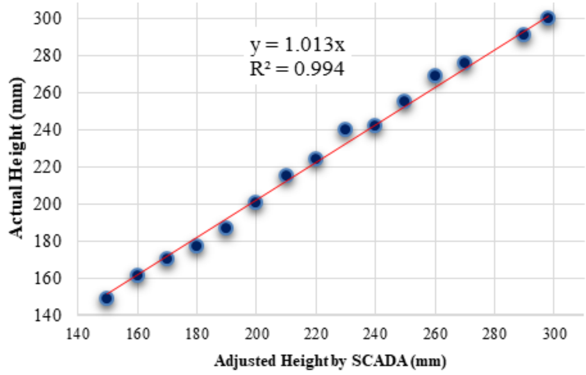

Fig. 9. Adjusted packaging height versus measured values

For packaging height adjuster unit, the R^2, ME, MAE and RMSE were obtained as 0.994, 10 mm, 3.53 mm and 4.57 mm, respectively.

3.3. Conveyor and fin-wheel speed

The speed of the conveyor was changed in the SCADA system in the range of 0.06–0.2 m/s with interval of 0.01 m/s and the response of the system was recorded in the database. In Fig. 10 in the square point, the conveyor speed has been increased by the operator with step of 0.01m/s and as can be seen, the actual values of the conveyor speed were equal to the desired ones. So the system can accurately adjust the speed of the conveyor based on the desired speed.

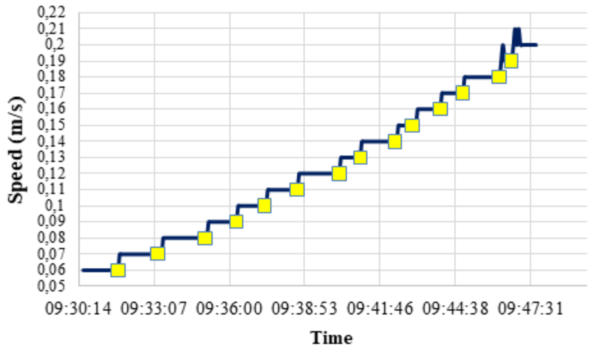

Fig. 10. Response of the SCADA system to changes in the speed of the conveyor in the range of 0.06–0.2 m/s.
SCADA, supervisory control and data acquisition

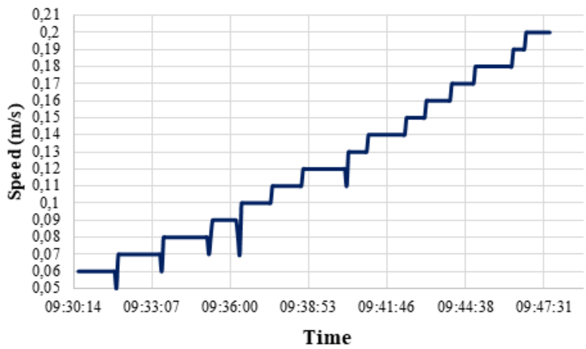

Fig. 11. The recorded values of the wheel sealing jaw speed as a function of the conveyor speed

The speed of the fin-wheel sealing jaw should be a function of the conveyor and so when a change happens at the speed of the conveyor belt, the system should adjust the speed of the wheel sealing jaw. Fig.11 presents changes in the fin-wheel speed that pursues the conveyor speed.

As shown in Figs. 10 and 11, the wheel seal treatment is exactly in compliance with the conveyor speed.

3.4. Temperature of sealing jaws

To evaluate the SCADA system in temperature controlling of the sealing jaws, the values of 125°C and135°C for vertical jaws and 170°C and 180°C for wheel jaws were used as the reference temperatures, and the response of the system was recorded. In designing of the heat elements, the desired time for heating the sealing jaws from room temperature (25°C) to reference value was assumed as 20 min. As shown in Fig. 12, the actual temperatures were linearly increased until reached the reference value. Upon reaching the jaw temperature to the value that has been set by the user, the system turns off the heating elements. The heating time (reaching to the desired temperature) was recorded at about 18 min, which was close to the chosen time (20 min). In Fig. 12, a fluctuation of 5°C and 3°C is visible for vertical and fin-wheel jaws, respectively.

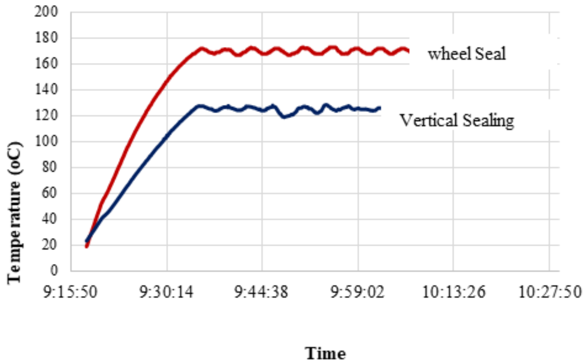

Fig. 12. Temperature changes in vertical and fin-wheel jaws at reference temperatures of 125°C and 170°C, respectively

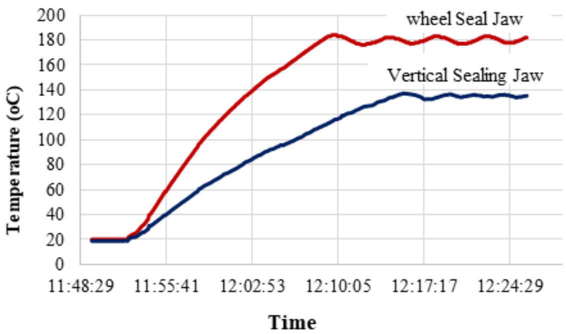

Fig. 13. Recorded temperature of sealing jaws at reference temperatures of 135°C and 180°C

Fig. 13 shows the recorded temperature of the sealing jaws at the reference temperatures of 135°C and 180°C. The needed time for reaching the reference temperature was recorded as 22 min and 20 min for the vertical and fin-wheel sealing jaws, respectively, which are close to the desired time (20 min). The temperature fluctuation of 3°C is observed in Fig. 13 for vertical and wheel seal jaws.

3.5. Gas injection unit

To evaluate the gas injection unit, the reference flow rate was changed in the SCADA system in the range of 1–10 L/min and 10–100 L/min with interval of 1 L/min and 10 L/min, respectively. Fig. 14 shows the first step of the experiment.

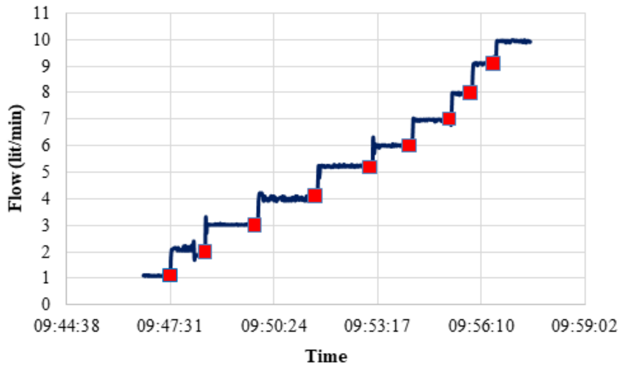

Fig. 14. Changes in injected gas flow rate in the range 1–10 L/min. Square points indicate that flow increment has been done by the user in the SCADA system.
SCADA, supervisory control and data acquisition

At this stage, ME, MAE and RMSE were obtained as 0.3 L/min, 0.08 L/min and 0.12 L/min, respectively. At flow rate of 0.3 L/min and 6 L/min, feedback of the system and modification of flow by SCADA are clearly visible.

Fig. 15 presents the response of SCADA to changes in injected gas flow rate in the range of 10–100 L/min. Square points determine times that the user increased the reference value of flow rate. For ME, MAE and RMSE, the value of 1.66 L/min, 0.557 L/min and 0.667 L/min were recorded. ME has occurred at flow of 100 L/min.

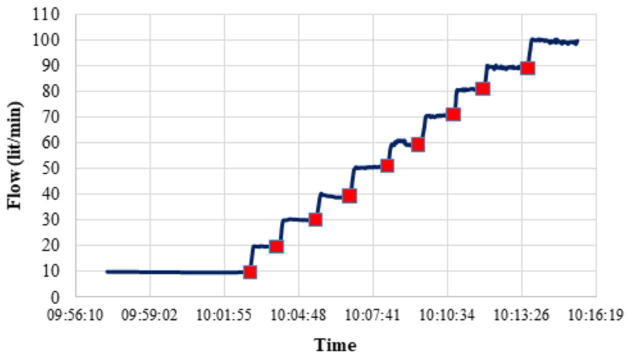

Fig. 15. Measured gas flow at different reference values adjusted by the user

Trend in the SCADA system provides graphs that help manager to supervise and analyse the system. For HFFS, four types of trends including temperature, speed, flow rate and digital parameters trend were designed. Operator can select each type trend and inspect probable problems. For instance, Fig. 16 shows the temperature trends that were recorded during the evaluation of the system.

Since alarms usually notify the user the events that are critical or harmful to a machine or process, so should be always visible for the user. In the developed SCADA system, alarms are shown

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at the bottom of the runtime environment (Fig. 16). In addition to displaying screen alarms, the occurred alarms are stored as a text file for a 24-h period.

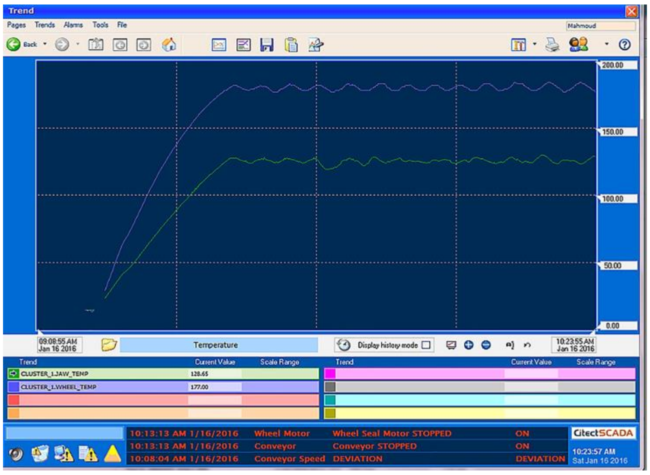

Fig. 16. Temperature trend of fin-wheel and vertical sealing jaws

3.6. The effect of MAP process on the shelf life

The evaluation of the fabricated apparatus was carried out using lettuce and cabbage. The packaged and fresh unpackaged products were kept in the same condition in a refrigerator. The pictures of crops were captured daily to evaluate the degree of corruption and decay. Fig. 17a–c shows lettuces on the 5th, 15th and 20th storage days. While no change was observed in the MAP process, the corruption of unpackaged lettuces was evident from the first sampling step, which increased when increasing the storage time. The corruption locations were flagged with yellow ovals in unpackaged lettuces stored for 5 days to make their visibility easier. Brown spots were seen in ones without packaging after 20 days. The obtained results for cabbage are similar to lettuce and the packaged products maintain their quality during the storage time. To keep the article concise, only the pictures of cabbages stored for 20 days were given in Fig. 17d. The colour and quality of packaged products were maintained during this period.

Fig. 17. Comparison of packaged (right side) and unpackaged products (left side) stored for (a)5, (b)15, (c)20 days for lettuce and (d)20 days for cabbage

4. CONCLUSION

In this research, the SCADA real system was designed and developed for supervisory control and automation of modified atmosphere technology-based fresh vegetable packaging processing. The developed system provides monitoring and process control, Human–Machine Interface (HMI), data acquisition and system troubleshooting. The monitoring system accurately reflects the performance of equipment. The system also generates appropriate alarms to indicate unusual issues with the equipment. Each alarm is accurately described, which allows for quick finding and eliminating defects. The use of SCADA allows for making remote adjustments such as packaging speed, polymer type and heat sealing temperature to optimise the system operation. The system provides the ability to carry out automatic packaging operations for a wide range of fresh vegetables. The data were acquired during the operation of the plant and displayed the current value of significant parameters in the form of appropriate tables and graphics. By using SCADA, we established supervisory management at different levels from sensors and actuators to computer systems and analysis of the acquired data. The most important advantages of SCADA in this project are the increment of productivity and the downtime reduction due to the increase in the visibility in each subsystem within the plant. It also provides the capability of monitoring the work in progress in real time and a better understanding of the production process, which decreases labour with improving quality. However, the life cycle assessment (LCA), which is the investigation and valuation of the environmental impact of a given product, is needed to be studied.

Nomenclature:

MAP	Modified Atmosphere Packaging
SCADA	Supervisory Control and Data Acquisition
HFFS	Horizontal Form-Fill-Seal
PLC	Programmable Logic Controller
DSP	Digital Signal Processor
RTU	Remote Terminal Unit
MTU	Master Terminal Unit
Lm35	Temperature Sensors
F	Gas Flow (L/min)
DOC	Digital Output Code of the Sensor
D	Sensed Distance (cm)
R^2	Coefficient of Determination
V	Output Voltage of the Sensor
ME	Maximum Error
MAE	Mean Absolute Error
RMSE	Root Mean Square Error

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HMI Human–Machine Interface
LCA Life Cycle Assessment
PC personal computer

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