UNIVERSITATEA  POLITEHNICA  DIN BUCURESTI
**Facultatea de Inginerie Electrica**

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# THE DOCTORAL THESIS SUMMARY

## CONCEPTION AND REALIZATION OF AN INTEGRATED SYSTEM OF MEASUREMENT, CONTROL AND DISTRIBUTION OF PHARMACEUTICAL DRUGS FROM A CENTRAL WAREHOUSE

## CONCEPTIA  SI  REALIZAREA UNUI SISTEM INTEGRAT DE MÁSURÁ, CONTROL SI DISTRIBUTIE A PRODUSELOR FARMACEUTICE ÎNTR-O UNITATE CENTRALA

Contents



**Keywords:** integrated system, pharmaceutical warehouse, electrical engineering, measurement and control system based on sensor networks, magnetic sensors, thin-film magnetic materials, iWSN wireless networks, autoevolution system, deep neural network, innovative system**.**

## PURPOSE OF THE THESIS

**The purpose of the thesis** was to analyze, optimize and integrate through an innovative holistic vision the physical infrastructure including numerous electromagnetic sensors, the IT infrastructure, as well as to implement the latest research on artificial intelligence (machine learning) related to an automated warehouse.

**The industrial process used as a case study is the management of a complex, highly automated warehouse for pharmaceuticals, practically a robotized system.**
Drug wholesalers face some challenges that can only be overcome by the use of optimized automated systems. Customers tend to make frequent, small orders and need customized services. On the other hand, companies tend to accept late orders, so they must ensure a quick and timely delivery, in very short time intervals. The waiting time is always tight. This applies especially for the drug distribution centers. The selection of orders means to find a number of products in the warehouse matching a number of independent orders of several customers. It is an important part of the supply and distribution chain, accounting for 65% of the total operating costs of a typical warehouse.

The system capabilities of top warehouses should be: automatic storage and pick up of transport boxes, without using forklifts and operators; bringing the products to operators automatically; automatic transportation of products from one pick up area to another; automatic routing of products to the right shipment station; allows the staff to operate in a hands-free environment; automatic weighing of packages and application of shipment tags; a single point of visibility and control over the entire warehouse automation system. **This thesis contributes to the fulfilment of this higher standard.**

The construction of the integrated pharmaceutical distribution system is described both from the economic and technological point of view, highlighting the practical requirements and improvements discussed in this thesis. **The study focused on the four systems using electrical engineering elements:**

1. **A distribution system** with the following work processes: customer order and its processing on a product picking line in common packages (totes), with a detailed description of the components (with pictures) and the workflow.

2. **A field data measurement and analysis system, to which we propose a major change, i.e. to implement a dual (magneto-optic) sensor network.** The dual network collects the tote data measured in the picking line (position in the conveyor line and tote identification), the operator carrying out the drug picking action, verification and validation of the picking precision and the conveyor belt speed. In this case, magnetic sensors have been added to the initial optic sensors to enable the identification of the tote and products through the insertion of magnetic tags using soft magnetic materials, in a thin layer and with a nanocrystalline structure; the thesis presents the characteristics of these materials in a special configuration.

   One of the biggest problems concerning the initial system was that the totes had only one barcode label that deteriorated real fast, leading to the generation of 20-25% errors during the verification of the activities carried out on the conveyor belt.

3. **An innovative regulation and control system**, with key components determined following the simulation and analysis of the processes taking place in a warehouse for pharmaceuticals, in an IT model using programmable objects [17].

   a. **An ERP system** integrating the activities carried out by the company supplied by this warehouse for pharmaceuticals

b. **The prediction system**, based on the basic neural network, used to optimize the warehouse processes - significant reduction of system and drug picking errors, while ensuring visibility of the potential to serve customers and anticipating the execution and delivery times.

   **The results have been significantly improved following the implementation of the dual sensor network**.

   The full use of the production facilities in conjunction with the market demand (customer orders) leads to a greater conveyor belt efficiency.

c. **The volumetric algorithm** (ERP, Warehouse Management System module) optimizes the arrangement of totes on the conveyor belt and the selection of the tote type (big/small), as well as the tote route to the loading (picking) stations based on the volume of drugs corresponding to the shipment order to be processed. The algorithm enables a smooth movement of totes on the conveyor belt and at the loading stations, so as to prevent blockages.

   The proposed system was designed to allow the existence and interaction of multiple control levels: (1) measurement and control hardware; (2) process computers; (3) central computing unit and warehouse control system interfacing with the warehouse management system; (4) warehouse management system.

4. **The actuating system**, comprising Schafer PLCs and actuators that drive the conveyor belt motor.

The functioning of the integrated system has been analyzed through repeated measurements, which highlighted the fact that the benefits are those expected and mentioned in this thesis.

## CONTENTS OF THE THESIS

The thesis has five chapters (last one for conclusions) that follow the logical steps of presenting, analyzing and developing a multidisciplinary subject, such as the optimization of a distribution system for pharmaceuticals. The thesis has two annexes and a bibliography.

**The first chapter** is an overview of an integrated distribution system for pharmaceuticals. The organization principles of a warehouse for pharmaceuticals are detailed here, with a focus on the characteristics of the sensors and transducers frequently used in this industrial environment. Apart from the monitoring system, the other component systems are presented in this chapter – the drug distribution and conveyor systems. A special attention is paid to the automatic control and regulation devices of the integrated system, with notions of artificial intelligence, expert systems and signal transmission. The electrical engineering elements – sensors, transducers, actuators, electrical actuators, applied informatics – are identified for detailed analysis to ensure an optimal functioning of the integrated system.

**Chapter 2** presents a selected distribution system for pharmaceuticals corresponding to a central warehouse of a major Romanian distributor of pharmaceuticals. The functional system architecture is presented from an industrial process point of view and the infrastructure elements to be modernized for an increased efficiency of the integrated system are identified. In this chapter, the thesis proposes the introduction of proximity magnetic sensors and the reassessment of the weighing sensors, diverters, motors and tensioners for the warehouse conveyor belt. The study was carried out according to the methodology indicated at the end of the chapter, including field specific analyses, the analysis of the integrated system architectural models and the experimental development activities.

**Chapter 3** presents the modeling elements of the complex distribution system for pharmaceuticals that make its analysis and optimization possible. The modeling procedure refers to the drug picking line within the warehouse and the IT application for the integrated system management. The detailed study of the models used for warehouse management allows for the identification of processes to be optimized.

**Chapter 4** presents and highlights the original approach of this thesis. The basic holistic approach enables the identification of the electrical engineering elements of this highly sophisticated, multidisciplinary hardware and software system and the correct specification of the interrelation with the other sub-systems. Improvements and additions are proposed as follows: the use of "fog computing" sensor networks, of proximity magnetic sensors, the introduction of tags using magnetic materials in a thin layer [14-16] and the use of a program based on neural networks for the automatic control of the conveyor belt operation. The proposed solutions are tested within the experimental framework detailed in the last sub-chapter. The experiment results under normal working conditions and in case of an error (no tag on the tote) prove the reliability of the artificial intelligence algorithms and a better data collection using the newly introduced magnetic sensors.

**Chapter 5** presents the general conclusions and the research guidelines. The last chapter highlights the powerful (scientific and technico-economic) impact of this thesis on the functioning of a real distribution system for pharmaceuticals used by a leading company on the pharmaceuticals international market.

The thesis ends with an annex containing terms specific to the pharmaceuticals industry and a second annex with the source code of the artificial intelligence motor developed by the author to increase the efficiency of the integrated distribution system for pharmaceuticals.

According to a study published in July 2013 [20], it is estimated that the global market for the distribution of pharmaceuticals will see a 8% increase of the compound annual growth rate (CAGR) (2012-2018) and will reach 85 billion US dollars by 2018. It is expected that the market will be supplied with non patented drugs and the generic drugs market will grow. The global pharma industry is rapidly growing due to the great number of technological innovations and the fast advancement in the manufacturing and implementation of these new technologies. These factors contribute to the increase of the global drug distribution industry.

**In this global context, this thesis plays a major role in paving the way to some new integrative, multidisciplinary studies.**

## WORKING METHODOLOGY

The **FIRST STEP** in the integrated design and development of automated systems and processes is the creation of a theoretical model, based on the latest scientific research. The latest research and developments regarding the self-evolution concepts based on evolutionary algorithms and deep neural networks in order to find the best solution to be implemented in the activity of automated warehouses.

Several sensor models that could be used for the picking lines of a warehouse for pharmaceuticals have been analyzed in order to find the most efficient solution. The conveyor line in the picking warehouse will be equipped with a dual system of magnetic and optic sensors, to determine the position of picking boxes (totes). The station used to verify the correct picking of products in each tote is equipped with a weighing sensor. The light-emitting diodes validate the data provided by the magnetic sensors. The barcode reader is also employed to identify the boxes of drugs in order to use the data related to each box (content and destination).

Even if different type sensors are present, **the magnetic sensor has priority of use in this automated system**, in order to detect the position of the box of drugs. Taking into consideration the operating conditions in a warehouse for pharmaceuticals, magnetic sensors are preferred due to their reliability, the accuracy of results offered during real time processes, but also due to the lack of errors caused by existing environment factors. Of the two types of analyzed magnetic sensors, Reed and Hall, the Reed sensors are preferred for determining the position due to their significant advantages [2].

Following the analysis, a Reed SME-8 relay proximity magnetic sensor has been selected for the warehouse for pharmaceuticals. An EK75 proximity photoelectric sensor has been chosen for the dual validation along the conveyor system in the warehouse for pharmaceuticals. A LOHET 1 Hall-type sensor will be used for the access gates. ICS-469-40 is the best weighing sensor for all the boxes (totes) in the conveyor system of a warehouse for pharmaceuticals.

**The conclusions of the study have already been applied to a warehouse for pharmaceuticals in Romania (Mediplus Exim). This analysis was vital for the management of the entire automation study process, from design and implementation to lifetime use.**

The **SECOND STEP** in the integrated design and development of automated systems and processes was the creation of a pilot model for the expert system required for the picking process, also using a simulation example to demonstrate the model functionality. The simulation results show that the expert system model basically meets the objectives and enables the performance and the optimization of warehouse processes.

The control system will include a central collection, processing and prediction system for the data measured inside the warehouse, **a system that will trigger the Schafer PLCs and the actuators, which in turn will drive the conveyor belt motors**.
At the central analysis and control system level, the delivery process and the actuation of the conveyor belts are carried out after the data are processed by a **neural network using self-evolutionary algorithms**. The optimized evolutionary algorithms described in this thesis derive from the research done for this study and represent the latest technological trend in the management of warehouses for pharmaceuticals.
The achieved results are useful for the development of industrial networks of magnetic sensors and identifiers in thin layers [18], the application of advanced industrial optimization methods based on artificial intelligence. Using a holistic approach, multidisciplinary pairs of sensor – processor – actuator – PLC can be fully integrated in the self-evolutionary system.

This study **complies with the main EU horizontal innovation R&D programmes**, especially Horizon 2020 and Europe Digital Agenda 2020. At the national level, the study is aligned with the National Research, Development and Innovation Strategy 2014-2020, the National Strategy for the Digital Agenda for Romania 2020 and the National Strategy for Competitiveness 2014- 2020.

As far as the **multidisciplinary character** is concerned, the study belongs to several domains: electrical engineering (including applied informatics), wireless networks of industrial sensors, massive parallel execution infrastructures for real time process management, artificial intelligence, pharma industry, industrial processes based on automated conveyor belts, logistics and distribution. A multidisciplinary characteristic of this study is the consequence of the scientific approach concerning the software modeling of the processes in a warehouse for pharmaceuticals, which involves engineering research projects, as well as the development of: sensor networks and dual measurement systems for the critical process parameters, intelligent decision-making support systems, intelligent systems with autonomous behaviour, unified hardware and software system for real time process management, reliable controllers for nonlinear processes, intelligent management systems, advanced support infrastructure systems for the intelligent real time monitoring of the industrial processes [9-12].

**The evolutionary algorithms** can be combined with other traditional simple or complex optimization techniques (such as the volumetric algorithm), enabling the parallel assessment of solutions and series processing of selections. This is better than other optimization techniques, such as searching within previous experiments and simulated improvement. The evolutionary algorithms can be used to adapt the solutions to the changing situations, since the traditional methods do not provide the expected results in case of dynamic changes.

Other relevant algorithms, e.g. evolutionary algorithms that can be combined with the system paradigms of evolutionary-fuzzy and neuro-fuzzy algorithms, which imitate the evolution of human individuals (unlike the concept of population used in the genetic algorithm) in nature, for the entire lifetime: learning by experience, legacy, gradual change and the accumulation of knowledge from routine operations.

The study challenges also derive from the traditional research approach resistance to change; thus, special attention will be paid to the exchange of information between the different disciplines involved, in order to integrate knowledge from different sources.

## INTEGRATED DISTRIBUTION SYSTEM FOR PHARMACEUTICALS

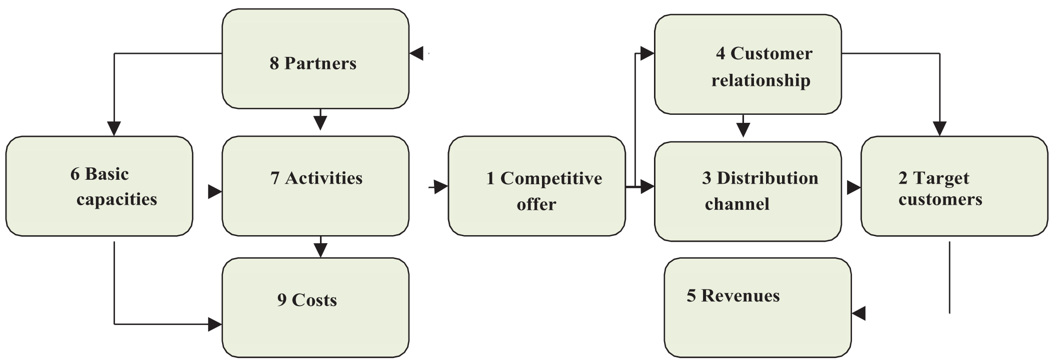



**Fig. 1** Logical diagram of the business model of a pharmaceutical distribution company

Focusing on the development and implementation of modern technologies for the warehouse management systems, based on a holistic approach, this study aims at optimizing processes for the whole value chain. "Industrial automation" requires a holistic approach and represents a challenge in the study of the complex behaviour pf systems as a whole. Obviously, a purely analytical research that aims at understanding systems by splitting them into smaller elements and their basic properties would not be enough.

Electrical Engineering elements are extremely important in this assembly.

In an industrial process, information is the values of the continuous variable parameters or the status of discrete variable objects (e.g. sensors, transducers, switches etc.). Information provided by the measurement and control devices are properly presented in order to understand the process and can be used to constantly optimize and change the entire activity. **It is thus clear that the measurement precision is a critical factor for the success of the designed system and a deep understanding of the sensor operation is required for a proper positioning thereof.**

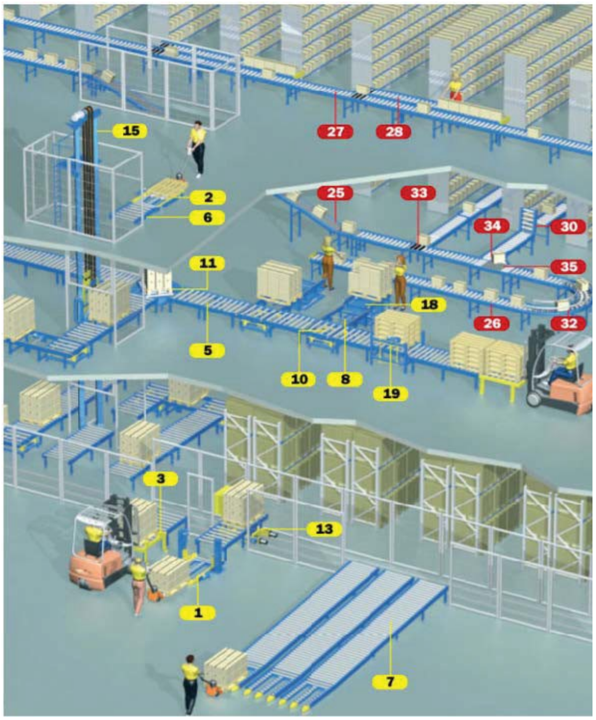



**Fig. 2** Warehouse for the distribution of pharmaceuticals

The distribution of a wide range of high-value pharmaceutical products poses special challenges. The customers (pharmacies, hospitals) have very high expectations regarding the delivery time (fast and frequent deliveries, sometimes several times a day) and the quality system puts great pressure on the warehouse operations. Customer trust and the observance of legal provisions (GDP/GMP standards) are critical requirements for the operation of a warehouse. Processes and equipment must be completely validated and have a flawless operation.

The automation of processes used by a pharmaceutical distribution company requires the implementation of an integrated ERP (Enterprise Resource Planning) business process management system interfacing with a real time WMS (Warehouse Management System).

If we take a look at Fig. 2, we can see that a bad warehouse management will lead to a global increase of expenses, generated by larger storage spaces, increased number of warehouse employees, more processing errors, but also by delayed deliveries, customer dissatisfaction and ultimately by losing customers to a better organized competition.

## THE INDUSTRIAL PROCESS. THE FUNCTIONAL ARCHITECTURE OF THE SYSTEM

- **Warehouse management system (WMS)**
- **Warehouse controlling system**
- **Processing units**
- **Hardware devices for measurement, execution and control**

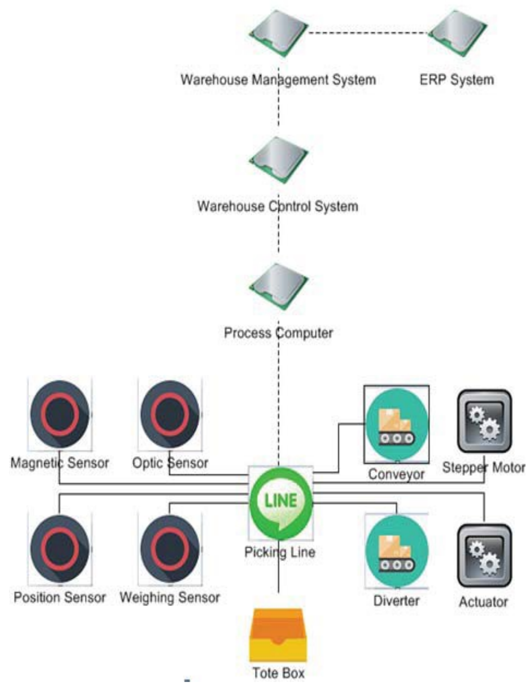



**Fig. 3** General architecture of the system

- **Level 1** is represented by hardware elements which make up the physical infrastructure necessary for the activity: transport elements, detecting elements (sensors and transducers), control elements (execution - magnetic actuators).

- **Level 2** is represented by the process computers that provide the interface between the automation hardware elements and the control system: it is taken over by the analog or digital signals from the various sensors and transducers of the system and ensures their conversion into digital information that can be processed by the information technology system for the execution elements, provides the take-over of the computer commands from the control system and converts them into execution instructions specific to each element

- **Level 3** is the warehouse control system and uses an IT application that provides the automated basic functionalities of the warehouse management system. Its role is to make available for the merchandise management system a series of high level functions related to merchandise movements in the warehouse.

- **Level 4** is represented by the warehouse management system (WMS) - the application which includes the logic of the merchandise movements in the warehouse: it takes over the sales orders from ERP and provides all the processes necessary to plan the deliveries (picking list, tour plan, volumetry) as well as for the actual delivery of goods to customers (picking, verification, packaging, loading). Transmits in real-time to ERP the stock level for the entire product portfolio.

The functions of measuring, execution and control hardware devices, which specify sensors, transducers, magnetic actuators, are the following:

**1- Proximity magnetic sensor** - Signals when the tote is in front of it.

**2- RFID sensor** - Reads the tag placed on the tote (the box containing the drugs on the conveyor belt). The advantage of this method is that the scanning of RFID tags in a radio frequency field does not require precise positioning of the object for reading since the radio frequency field penetrates any nonmetallic material so that no direct contact is required between the RFID tag and the reading equipment.

**3- Optical sensor –** Validates the value measured by the magnetic sensor (double-check system).

**4**. **Barcode reader –** Validates the value read by the RFID sensor on the tote identifier

**5. Weighing transducer** - Measures the pressure exerted, thus checking the presence of drugs in the tote by adding their weights

**6. Diverter –** Deviates the tote from the current conveyor belt to another band

**7. Stepper motor**- Drives the conveyor belt elements which ensure the movement of the totes on the circuit.

**8. Position sensor –** Senses the presence of the magnetic code and determine the tote deviation from one conveyor belt to another. The deviation from one conveyor belt to another is made by means of a diverter. For this installation, either magnetic sensors based on the Hall effect or Reed connectors can be used as proximity sensors. Validation of the transmitted information will be done by comparing the signal with that emitted by the optical sensors.

**9. Actuator** - Transforms, amplifies and transmits motion, measuring specific parameters: rotational speed, position, quantity.

## OPTIMIZATION OF SYSTEM CONTROL BY MODELING

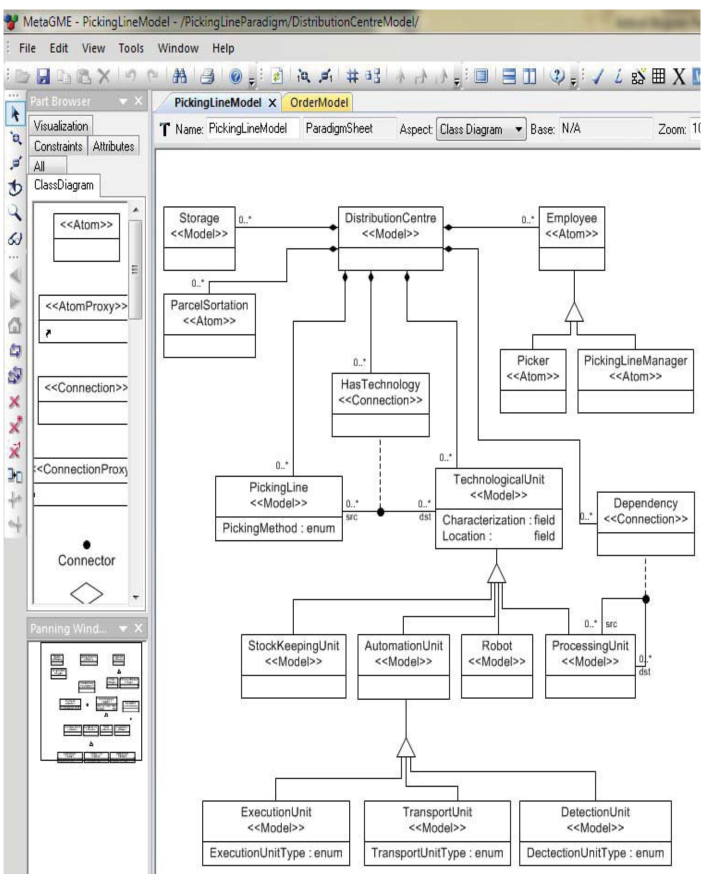



**Fig. 4** Modeling of the picking line (for products picking)

For the system analyzed in this thesis, the picking process was simulated using a discreet deterministic model implemented with AnyLogicTM, considering the forklifts and their operators, whose routing was optimized in a simulation environment based on HeuristicLab.

The transport from warehouse to workstations was treated dynamically and taking into account the distances and resources available as constraints of optimization, and it was considered that it could be improved by a stochastic model. Route optimization has been performed with a genetic algorithm, which is similar to Dynamic PDPTW (Pickup and Delivery Problem with Time Windows).

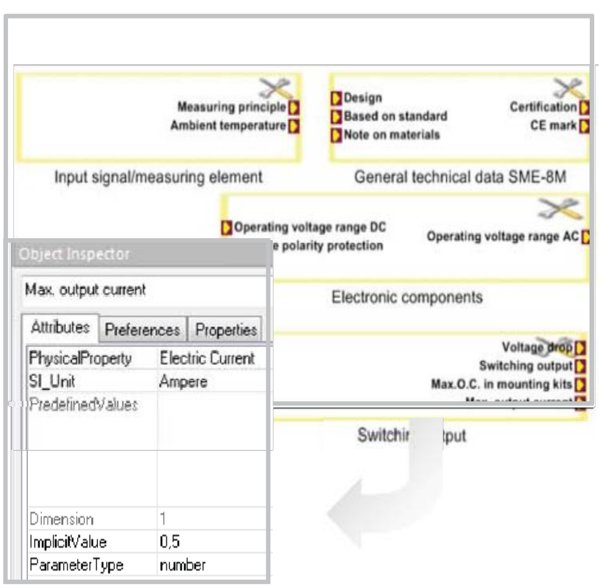
For simulation of the functioning of the analyzed system, a stochastic model was applied to the flow of picking orders, considering the probability that a picking request would occur at a given location and taking into account the space between the locations. Therefore, the distance and the walking time were estimated for three design configurations: single warehouse, double warehouse with conveyors and warehouse with conveyor and RFID (radio frequency identification). Their simulation demonstrated that a decision of investment in technology must take into account the frequency of picking and the homogeneity of the picking stations

The proposed modeling language contains three important parts/models:

- **OrderModel**, includes a hierarchy of elements for modeling the different technological units which accompany this part of the data system, such as: detection units (which are the abstract representation of sensors, bar code scanners or RFID readers) or execution units (electric motors, actuators, printers, sealing machines).

- **PickingLineModel**, modeling of the picking lines: is a generic characterization for measuring instruments and systems and has been previously used in a data integration environment called EquiLAB [6]. Its purpose was to create a library of models which can be used for data obtained from non-homogeneous parsing sources and integrates them into a common database for further processing.

- **Tools**, a class of objects imported and reused in this study.
  It was obtained a visual representation of the warehouse system, whose complexity has led to a collection of interlinked diagrams using the concepts of the picking line modeling and by adding specific representations based on the "Tools" class of objects for automation, warehousing and transport and execution units, in accordance with their technical specifications.



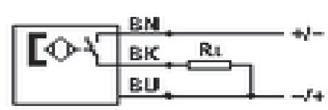



**Fig. 5** Description of the technical data of a proximity magnetic sensor type Reed.

As an example was used a Reed type magnetic relay, which has a simple construction and consists of

a switching contact which is placed on a bracket of a U shaped casing.
On the other bracket is mounted a permanent magnet. When a metal object passes through the brackets of the casing, shielding of the magnet lines of force occurs, determining the modification of the relay state.

Such a proximity sensor [7] can be modeled using the «Tools » class, based on the capabilities of data acquisition or to adapt to different settings (see Fig. 5).

The editor supported the generation of a hypertext description by exporting the entire model, with multiple diagrams, into a single XML (Extensible Markup Language) file. This feature is important for further integration with other systems, such as EquiLAB for data integration, but also with various other systems for optimizing the configuration of automation elements of the picking line and of the associated processes.

**Formal representation of warehouse architecture is essential for real time monitoring of many devices which control its operation, early detection of errors, and additional system log analysis to improve processes and overall system quality.**

## PHYSICAL INFRASTRUCTURE OF THE EXPERIMENTAL ENVIRONMENT

The analysis of the warehouse for drugs revealed several areas of intervention in the industrial process. Among these, we have identified from a technical and functional point of view **the main elements of Electrical Engineering that can contribute to the modernization of the pharmaceutical distribution system**.

Currently, **the operating mode for the industrial environment** is: an order is entered into the system, and one or more totes are then assigned to that, which start to travel on a conveyor belt to the picking stations. The presence of the tote is checked by means of a group of sensors (optical proximity sensors). Operators store the items required in the order attached to the tote when they arrive at the picking stations, picking up the products from the shelves where they are stored. Then the totes go to a check area where they are weighed to check, in a quantitative manner, the presence of all the necessary items. Upon successful completion of this test, they advance to the sealing and delivery area, where they are taken over from the conveyor belt by other operators and shipped to their final destinations.

Following the analysis and the description of the innovative solution architecture **we have identified a significant number of deficiencies in the standard industrial** management system of the order, from issuance to shipment, such as:

1. The position of a tote in the system cannot be tracked with good accuracy, in order to observe in advance a route error or a possibility to optimize it in case of a blockage at a particular picking station.
2. Lack of a correlation between the operator who processes the order and the tote to be processed, which hinders the tracking of the tote and may cause some errors during its processing;
3. The existence of a single method for verifying the integrity of a processed order (weighing method);
4. Existence of a single tote tracking method across the conveyor belt, by barcode labels and optical reader (which are broken-down / damaged in the industrial environment).
5. A product theft from the warehouse can only be proven by physical control.

In the following we will explain **an improvement solution for the industrial environment with a range of sensors and transducers**, designed to remedy these shortcomings and to improve the efficiency of the activity.

## MODERNIZATION OF THE PHARMACEUTICAL DISTRIBUTION SYSTEM

Goals concerning the modernization of the system:

- **Detection of processing errors by means of dual magnetic-optical sensors network** and correlation of the beacon type sensors for operators with box / belt sensors and implicitly predicting potential errors. Inferential and predictive analysis will be done with modern methods, based on decision trees so that the system administrator subsequently understands the process / situation / factors that generated the error.

- **Continuous analysis and collection of telemetry information from an advanced sensor network** which combines magnetic, optical and mechanical sensors at the belt level, magnetic and RFID sensors at the level of the box conveyed by the belt, magnetic sensors, RFID and beacon type sensors for the operator. Therefore, a deep neural network will be used to predict the completion times of a command by continuously analyzing the data stream across the sensor network. The system will evolve continuously and will take into account all the operating parameters of the industrial process, from aspects such as fluctuation of staff depending on the period of the year, the reactivity / responsiveness of the employee to the types of orders and clients served.

- **Making a magnetic-optical-mechanical assembly combined with artificial intelligence** to reduce the error rate in the process of loading / orders processing. System data will be generated from the sources as:

a) the mass sensor placed on the belt analyzing the total weight of the box / tote,
b) industrial optical camera (NVidia Jetson TX1 / TX2 range) placed above the belt, which films the contents of the box / tote at a specific control point. Finally, a deep convolutional neural network will be used to detect load errors through visual recognition and by analyzing additional parameters.

***Selection of sensors for the requirements of the warehouse for pharmaceuticals.***

The proposal is focused around **the expansion of the current installation, at the level of conveyor belt, warehouse and human operators with sensors and transducers of magnetic or electromagnetic type**. The proposal includes two types of devices, analyzed in detail in a further section, divided into two categories, magnetic and electromagnetic targets ("tags"), further classified as identifying devices and readers equipped with antennas for these identifiers, classified as intelligent sensors (the claim is supported by the fact that they process and transmit the data further to a server).

Specifically, it will be used **two types of identifiers: thin metal alloy films and radial antennas in RFID technology** (short range radio identification). The first type is proposed to be placed at the level of totes and products, due to its small size, and the second type will be placed at the tote level as well, but also on the shelves with the products, next to them. **The antennas** corresponding to the interaction with the two highlighted technologies will be located at the following key points: a) at the conveyor belt level, with sufficient frequency to identify and position with good accuracy the totes travel within the warehouse; b) at the level of human operator, in the form of a bracelet, to ensure a correlation between the products removed from the warehouse and the processed orders, but also; c) at the level of access points in the warehouse, to prevent any malicious intent.

Increased attention has been paid to the selection of the method of expansion of the current installation, as well as to the technologies used, so as **to ensure the specific restriction of an industrial environment of interference and electromagnetic compatibility**: the magnetic and electromagnetic elements are of short radius (<1m), in order not to interfere with other electrical or electromechanical devices currently used.

The sensors used are equipped with antennas for interacting with tags, previously described as proximity sensors, and will communicate wherever possible via a **wired interface to avoid interferences**. However, bracelets used by operators will communicate in a wireless technology [1], but in a spectrum that avoids common frequencies (2.4 GHz, 5 GHz and generally everything in the GHz spectrum), all for reasons of diminishing the interferences and spectral congestion associated with the multitude of mobile devices operating in this area.

Another important aspect involved in this proposal is the aspect of device related costs, so most of the objects from the warehouse are equipped with passive tags (no power or complex operation logic), with low acquisition or maintenance costs, with active devices being used only in locations where they are absolutely necessary (at the level of human operator, conveyor belt or access points).

***Description of the architecture***

According to the above and taking into account the current architecture, we emphasize that this is thought to be transparent to those involved in this process. Hereinafter, the devices involved are exemplified in accordance with the following convention:

- Magnetic type antennas, with soft alloys thin layer, are represented as a wavy line.
- Antennas for RFID technology are represented as a spiral. The proposed architecture is divided into three layers, exemplified suggestively in Fig. 6

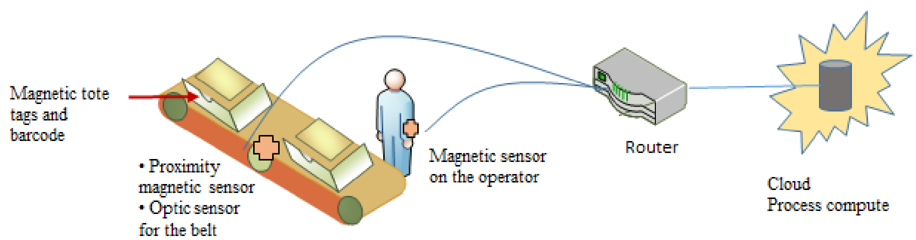



**Fig. 6** The proposed architecture

**We will continue to discuss the approach and improvements at the level of belt / operator for the processing environment and the cloud type analysis, as well as at the intermediate interconnection level, described below as a router.** The three levels are in a permanent connection in order to provide all the information needed for the analysis, with mechanisms for error and redundancy handling using the cloud communication method implemented in every point.

A) Inside the warehouse **we propose to place the metallic films above the devices / totes**, due to the reduced dimensions and to the advantages described above. **Next to each product section, we propose the positioning of RFID tags** to make the correlation between the product picked up and the operator responsible for processing (Figure 7). Therefore, are provided both the quantitative information about the targeted item with the help of the first tags, as well as qualitative information, respectively which of the items are currently processed.

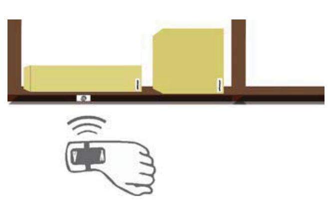


**Fig. 7** Sensor positioning on shelves and at the operators' wrist

B) Next, according to the way the order is carried out within the warehouse, the totes are initially equipped with barcodes only. **The totes shall be equipped with thin films, placed behind the barcode** which shall provide the physical need for the new features proposed for implementation. **The position allows both interaction with sensors arranged at the belt level, as well as with the bracelets carried by the operators** (Figure 8). The choice of positioning on the elements concerned took into account the specific needs of magnetic technologies, namely the short operating range.

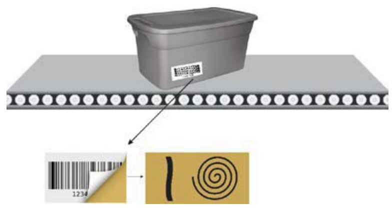


**Fig. 8** Sensors placement on the tote

Information on local interaction between moving items within the warehouse must be sent to the cloud; for this, **we propose to install routers for iWSN networks at different points inside the warehouse** in a strategy exemplified in Fig. 8.

As a result, the proposed sensors solve these problems, and there can be noticed that:

1. for the human operator, it is proposed to place a *"beacon (custom built)"* in the form of a bracelet that provides the system with information about space positioning and the interaction with the totes;

2. during the experiment was found the possibility of extending the entire proposed system with a new innovative subcomponent consisting of an industrial camera and a built-in high capacity computing device. Practically, in order to check the integrity of the totes, it is proposed to place some modules with cameras for visual inspection of all products - the NVidia Jetson TX1-based module, or the TX2-based module, capable of autonomous information processing and capable of supporting a neural network

3. equipping totes with RFID sensors to provide multiple tracking methods and interaction with the human operator.

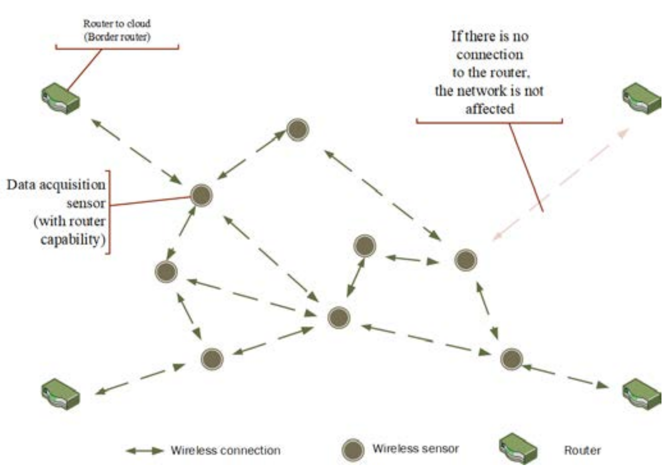



**Fig. 9** General iWSN diagram

**The reasons for the choice are**: low power consumption of the devices type *beacon* for operators (to ensure functionality over the entire work hours), RFID tags for selected totes because they are transparent in the operator's usual activity (they interact with the tote by proximity, without additional effort, do not need to use a barcode reader specifically to the area of interest) thus providing extra data without sacrificing performance. The proposed tags are distinguished by the high speed of interaction (up to 8 tags per second), the amount of information they can store (up to 144 B), IP68 certification, high temperature resistance, resistance at mechanical shocks or other factors encountered in the industrial environment.

***Parameters and physical characteristics of the iWSN network***

According to the previously described structure, there is a larger number of routers, so that the signal can be taken from any point of the warehouse, and in the event of a routing device failure, the others still provide a connection to the server. Moreover, because we are talking about an iWSN network, the sensors located have internal routing capabilities, becoming themselves routers when needed (one of the devices is not within a router's range but is still in the proximity of another device which in turn is within another router's range). It can be seen that this configuration, referred to hereinafter as a mesh network, has a low error rate compared to a classical star topology (with a single router and sensors without routing capability). The range is expanded, offering more modular ways of communication of the accumulated information (increased redundancy) (Figure 9).

The infrastructure described in Fig. 9 is based on a number of routers to ensure connectivity to the cloud, the proposal being: Firefly 6lowPAN platform. The module provides connectivity between a classic wired network and a network of sensors type mesh. The communication channel between sensors and routers is Zigbee or BLE technology, being protocol-compatible. Wireless sensors use the SensorTag platform, interfaced with the RFID modules described above.

***Technical description of the network of sensors***

Hereinafter we will present the technologies involved in the proposed architecture for the sensor level, their defining features, the advantages presented, as well as how they are characterized or what is their behavior in the event of errors.

Starting from the interface between the moving or stationary objects to be identified, we will use magnetic technologies for nanocrystalline films and RFID tags. The main technical features are presented below.

**A) The RFID tags -** use electromagnetic principles, by which a passive device (an antenna connected to an integrated circuit) uses the energy radiated by a reader to be powered up and to transmit data.

The advantages for this application are:
*a) The short interaction range* (1-10 cm) ensures that there is no interference with other electrical and electromechanical systems located in the industrial environment.
*b) Anti-collision function* - when there are several tags in the proximity of the reader, one can distinguish between them in order to be read one by one.
*c) Error handling*, at the hardware level, in the integrated circuit inside the tag it is implemented a program with finite states to handle errors occurring in any of the operating states (detection, data transmission, command interpretation)

**B) Thin, nanocrystalline magnetic materials (films)** are used to detect certain objects in an area of interest, having the following characteristics:
*a) 1-2 m interaction distance*; in the case of permanently powered readers, the resonating field generated by the magnetic tags may be detected from a distance that is enough to ensure the

environment necessary for the conditions specified previously.

*b)* Given that there is no circuit integrated with logical functions at tag level, we can state that, if the detection antenna is sized appropriately, there will be no errors.

**For the completion of the network of standard optical sensors with magnetic sensors and the setting-up of the network of magneto-optical sensors, the following shall be considered:**

1. For the interfacing system with tag type magnetic sensors the use of the following devices is proposed:

   i) NFC modules capable of reading/writing tags such as: EZ430 from Texas Instruments or T3H2111 from NXP Semiconductors.

   The readers are characterized by the large range of operating temperatures, FCC and EC certifications for secure operation and multiple interfacing capabilities (SPI/I2C) with the wireless sensors described below:

   Another important aspect is compatibility with multiple ISO standards, ISO14443, ISO15693 and ISO18001 among others, ensuring easy scaling to multiple tags from different producers (should a tag become unavailable, an easy transition may be made to another supplier/type).

   i) Proposed tags: NTAG210; NTAG213.

   These are available in different shapes and are characterized by the following features: operating temperature between - 40 and 200 degrees Celsius, resistance to corrosive agents, IP68 certification, fast interaction time (<200μs), hardware implementation for anti-collision in order to avoid false scanning.

2. Alternatively, we can explore a new direction, with UFH tags and readers (frequencies close to 1GHz). This alternative is not proposed in the experiment, but it can be considered as an alternative.

3. In order to comply with the requirements for traceability/positioning of human operators, the experimental proposal is the following:

   802.15.4 ad (wifi routers with internal positioning capability) for which the sensors are made up of:
   - solution for the supply management and Li-Ion battery (>2000mAh, JEITA compliant)
   - processing and connectivity in a single chip (of the cc3200-type) (the fact that the solution has a high integration level, FCC compliant represents a great advantage), magnetic interfacing with an active reader implemented with the help of TRF7960A or PN7120 (to support as many standards as possible: ISO14443, ISO15693, ISO18001), according to those described in the previous point.
   - Bluetooth, low capacity communicator.
   - CC2650 processor, also used for integrated communications.

**In conclusion, for the completion of standard optical sensors with magnetic ones, a combined infrastructure is proposed, in which sensors share the same processing and communications hardware architecture.**

## THE ARCHITECTURE OF THE NETWORK OF MAGNETO-OPTICAL SENSORS

The proposed approach is based on the principle of scalability. In the following section we will describe the architecture that ensures a good and reliable data flow for the software environment that makes decisions. To ensure the technical support for the goals described previously various **data from the industrial environment** must be collected:

- **real time position of the totes**/merchandise transport boxes during their movement; the totes are moved inside the warehouse with the help of conveyor belts, being directed towards the picking stations. In order to follow their route on the conveyor belt, the totes have barcodes applied, are scanned regularly at decision points along the route, with the help of optical sensors.
- **real time position of the operators** in the area of the warehouse, using a state-of-the-art technology to locate them inside the building, where classic positioning technologies such as GPS do not work. The implementation may be done using the existing WiFi connection points in the location, if the software allows it (they are compliant with the IEEE802.15.4a standard).
- **operator-tote correlation** in order to observe the order progress in real time, thus ensuring the correspondence between the actions taken by the operator at the time of receiving the order related to the tote, in order to minimize the reception time, as well as to optimize efficiency.

***Magnetic proximity sensors***

These sensors signal when the tote arrives in front of it (the tote is the box containing the drugs on the conveyor belt). In order to signal the tote arriving in front of it, the sensor must be a proximity sensor. The distance at which these sensors detect objects is called "detection distance". The lack of actual contact with the sensor ensures high reliability and a small error rate. These sensors may be: inductive, capacitive, magnetic, ultrasound, optical. The output signal of proximity sensors reveals only the presence or absence of an object within the nominal detection distance of the sensor. Consequently, the electric output signal shall be an on/off type signal.

Even if different type sensors are present, **the magnetic sensor has priority of use in this automated system**, in order to detect the position of the box of drugs. Taking into consideration the operating conditions in a warehouse for pharmaceuticals, magnetic sensors are preferred due to their reliability, the accuracy of results offered during real time processes, but also due to the lack of errors caused by existing environment factors. Two types of magnetic sensors were analyzed; by the physical effect at the basis of their operation the following were chosen:

- magnetic proximity sensors with Reed relay
- magnetic proximity sensors with Hall effect

The models made with Reed contacts are preferred due to reliability and reduced costs. They have a low switch speed (up to 50Hz). The Hall effect ones can switch at high speeds (up to thousands of Hz).

***Magnetic proximity sensors with Reed relay.***

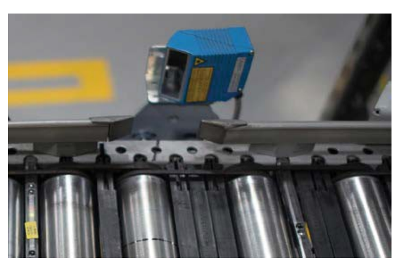


**Fig. 10** Example for installing proximity sensors on the conveyor belt of the picking line

## INFRASTRUCTURE ELEMENTS FOR BRINGING THE SYSTEM UP TO DATE

For the operators at the location we propose an intelligent processing node, equipped with RFID connectivity for interaction and picking data in their proximity (interaction with the tote), but also a RF connection for sending the data to a border-router and calculating the position vector in space. The router has a special construction, to substitute the needs specific to the industrial pharmaceutical area. The key features for the device are: resistance to interferences specific to the industrial environment in the usual radio frequencies (2 - 5 GHz), completely avoiding the regular frequencies so as not to cause spectrum congestion, optimizing data transmission in order to obtain an increased battery lifetime.

- **real time position of the operators** in the area of the warehouse, using a state-of-the-art technology to locate them inside the building, where classic positioning technologies such as GPS do not work.
  The implementation may be done using the existing WiFi connection points in the location, if the software allows it (they are compliant with the IEEE802.15.4a standard)

- **operator-tote correlation** in order to observe the order progress in real time, thus ensuring the correspondence between the actions taken by the operator at the time of receiving the order related to the tote, in order to minimize the reception time, as well as to optimize efficiency.
  For the operators at the location we propose an intelligent processing node, equipped with RFID connectivity for interaction and picking data in their proximity (interaction with the tote), but also a RF connection for sending the data to a border-router and calculating the position vector in space. The router has a special construction, to substitute the needs specific to the industrial pharmaceutical area. The key features for the device are: resistance to interferences specific to the industrial environment in the usual radio frequencies (2 - 5 GHz), completely avoiding the regular frequencies so as not to cause spectrum congestion, optimizing data transmission in order to obtain an increased battery lifetime.
  The actual implementation of the wireless sensor network implies **three types of devices**:

- **Routers** capable of collecting information from inside the industrial environment and making the connection to the cloud for further processing. Taking into account the fact that the industrial environment is the loudest and has the hardest working conditions as opposed to a household environment, routers must comply with additional requirements: autonomy in the case of a power cut, local storage in the case of no connection to the cloud, high RF signal in order to cover the target areas (large areas). The technology must ensure a minimum communication of the Ethernet-type (cable internet), as well as GSM (for redundancy, should there be no local connectivity), and for communicating with the nodes in the warehouse we recommend using a ZigBee-type technology (IEEE 802.15.4) or narrowband WiFI (IEEE 802.11ah)

- **Nodes** to collect the information from the target sources (totes, conveyor belt or human operator), developed in order to cope in the conditions described above. These must be equipped with the corresponding technology in order to communicate with the access routers, to ensure increased autonomy so as not to interrupt the data flow in the middle of the operation process (we refer to multiple source supply: battery, low or high voltage, depending on availability). Also, in order to ensure increased connectivity and reduce the risk of data loss, the nodes are capable, depending on the chosen protocol, of communicating with each other, becoming routers themselves, thus having the advantage of an increased area for installing the devices, as well as data transmission redundancy in order to avoid loss of data due to transport. Also for nodes, we wish to implement communication capabilities through short range RFID technology, in order to ensure connectivity with the magnetic sensors installed on the totes.

- **Passive magnetic sensors**, installed on totes or on product packaging, are meant to offer positioning information for nodes. The sensors were chosen especially in order to cope with the industrial environment.

- For already existing optical sensors, new sensors shall be installed as relays (they only collect the data from those already installed, without affecting the current infrastructure**).**

## *THE SELF-REGULATING SYSTEM*

The whole approach proposed is based on using deep neural networks for experimental research and development of a model of the type assembly of agents with automatic learning that **can solve the following problems** by continuous learning and auto-adaptation:

- Determining the optimum time for an industrial process based on a set of objectives-tasks
- Determining the optimum parameters for an industrial process based on a set of objectives-tasks
- Auto-adaptation to the changes in the industrial ecosystem without the need for human intervention

The predictive self-regulating system has **four major components**:

- **The dual sensor system** that collects the data regarding the tote measured on the picking line (position on the conveyor belt and tote identification), the operator performing the operation of picking the drugs, checking the accuracy of the picking operation and the conveyor belt speed.

- **The prediction system**, based on the deep neural network, whose role is to optimize the operation of the processes in the picking area, significantly reduce errors in the system and concerning drug picking, further ensuring visibility of the potential to serve customers and of the execution times.

- **The volumetric algorithm** (ERP, Warehouse Management System module), optimizes the arrangement of totes on the conveyor belt and the selection of the tote type (big/small) based on the volume of drugs corresponding to the shipment order to be processed.

- **The actuating system**, comprising Schafer PLCs and actuators that drive the conveyor belt motor.

The system is self-regulating and is defined by the entry and reference size (r), the exit size (y) and perturbation factors – see Fig. 11. The role of the prediction algorithm is to ensure a value as close as possible between the predicted size and the exit size, the prediction percentage error being of maximum 5%.

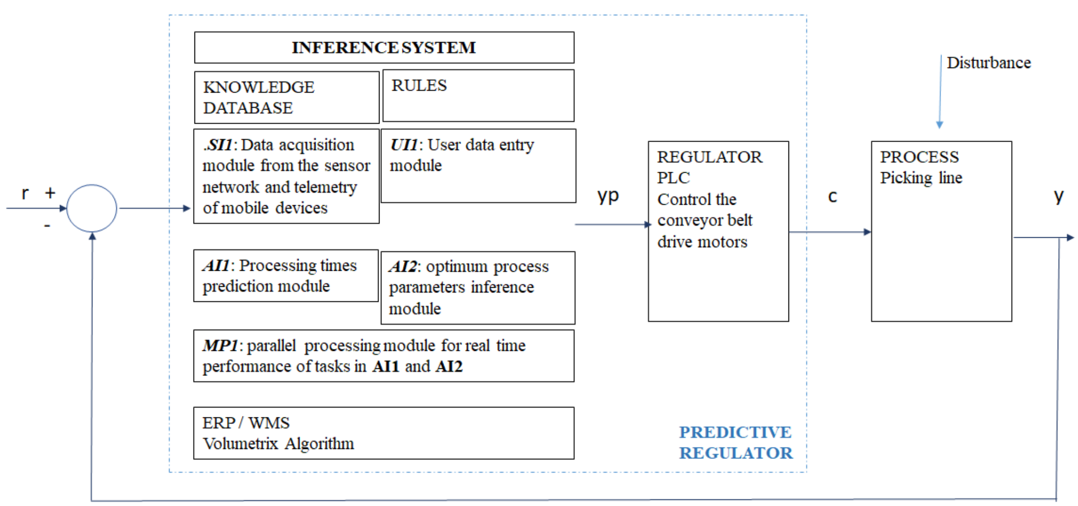



**Fig. 11** The structure of the automatic predictive self-regulating system;
r – reference size; c – order; y – exit; yp – predicted exit

*CONTROL ALGORITHMS. MODELING THE NEURAL NETWORK*

During the following we will present the mathematic model for analyzing the information and inferring decisions, based on learning with reverse propagation in deep neural networks [8]. According to the previous description, this model shall receive the data generated by the sensor network, combine said data with those entered by human operators and **shall make the following operations**:

(1) auto-adaptation by real time learning (on-line learning) of the changes in the operating parameters of the sensor network or of other elements in the production environment (warehouse for pharmaceuticals)

(2) generating real time predictions/inferences regarding the optimum sequence of operations necessary to reach a certain objective; thus, in practice, in the case of automating a warehouse for pharmaceuticals, there is the need for an inference regarding:

- optimum routes at mobile machine level,
- optimum sub-routes at human operator level,
- optimizing picking-list,
- choosing the ideal human operator for a certain picking-list structure, and so on.

| | |
|---|---|
| ***.SI1***: data acquisition module from the sensor network and telemetry of mobile devices | ***UI1***: user data entry module |
| ***AI1***: processing times prediction module | ***AI2***: optimum process parameters inference module |
| ***MP1***: parallel processing module for real time performance of tasks in ***AI1*** and ***AI2*** | |

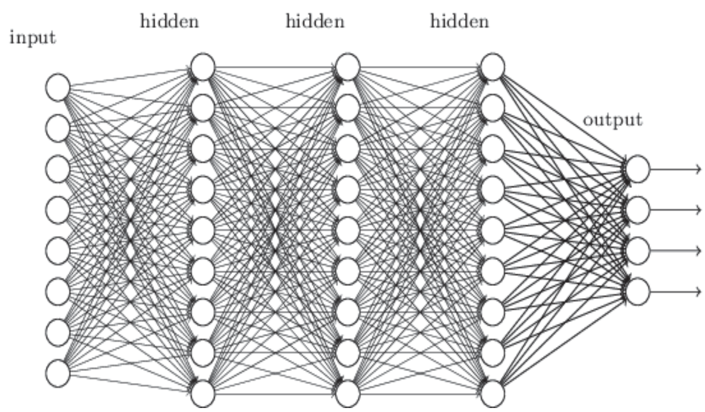



**Fig. 12** General structure of the integrated system

## EXPERIMENTS PERFORMED

Regarding the approach of the entire experiment, we started from the real time operation of the system in the production environment. The configuration of the experiment took into account both the basis from which we started, a system based on a classic operation model, and the innovations proposed by this study. The main elements that were analyzed are closely connected to the main objective of using the proposed magneto-optical assembly combined with artificial intelligence for the detection and implicitly the reduction of the error rate in the order loading/processing process.

Thus, the analyzed data came from the following sources:

1) beacon-type operator sensor for the identification of the operator-picker, both spatially and temporally;
2) optical sensors for interrogating the box (tote) placed on the belt
3) magnetic sensors for interrogating the box (tote) placed both on the belt and in other areas in the industrial space, where the cyclical tote loading process takes place (order preparation)

In terms of the experiments metrics, the following data were analyzed, starting from the primary data and ending with visualizing the variation of the experiment indicators:

a) The entry data generated by individual sensors (both magnetic and optical, according to the dual nature of the sensor network proposed)
b) The prediction data generated by the innovative system proposed
c) The primary results obtained in the experiment (real data vs. predicted data)

The experiment performed was made up of **two sub-experiments** carried out on two different structures of industrial belts.

**a) The first sub-experiment** used only optical sensors and introduced disturbances in the operation of the belt (the tote barcode label was damaged).

**b) In the second sub-experiment** we used the same industrial belt structure, to which we added magnetic sensors and implicitly the readings they obtained, keeping of course the damage to the barcode label at a certain point in the process.

In order to define the experiment more clearly, we shall present below the relational table structure of the data processed in the innovative system using a subset for analyzing the experiment carried out.

**The first data set analyzed** is the one generated by the sensors installed in the complete process of the belt in the warehouse. The analyzed information refers to:
**ID**: measurement (observation) identifier
**SensorID**: identifier of the sensor that generated the information for the identification of the tracked cart
**SensorType:** type of sensor used – optical (O) or magnetic (M) for the respective industrial belt segment. In the example above only optical sensors were used.
**Time**: time stamp generated by the sensor
**TimeDelta**: time variation from the stamp generated previously by the previous sensor in the sensor sequence (the time necessary for the industrial belt segment to be completed)
**ToteID**: tote/box identifier
**Picker**: human picker responsible for the respective cart on the given segment of the industrial belt

| ID | SensorID | SensorType | Time | TimeDelta | ToteID | Picker |
|---|---|---|---|---|---|---|

| ID | SenzorID | TipSenzor | Time | TimeDelta | TotaID | Culegator |
|---|---|---|---|---|---|---|
| 1 | 4393724 | O | 2016-02-10 07:33:28.363 | 0 | 32004210 | 4081 |
| 2 | 4393731 | O | 2016-02-10 07:34:29.657 | 01:01.294 | 32004210 | 9692 |
| 3 | 4393747 | O | 2016-02-10 07:36:48.987 | 02:19.330 | 32004210 | 9593 |

**Fig. 13** The first data set - data provided by the sensor network regarding the movement of the conveyor belt

As for interpretation, the first data set analyzed represents the checking of the tote in front of each sensor (optical or magnetic) for a predefined route containing 15 sensors. In terms of the system, no other information is necessary from the respective sensors apart from sensor identification as such (SensorID) and the time stamp generated by the sensor when the tote passes/is identified. At this point we point out the **need for using a dual magneto-optical sensor network**. As discussed in the architecture section, the tote contains both the visual identifier (barcode) necessary for optical sensors, and the tag necessary for magnetic sensors.

**The second data set** contains the available information regarding the content loaded in the tote, whose route was completed previously (according to the first data set). The encoding of the information associated to the tote refers to product characteristics:

**pId**: product identifier
**L**: product length (cm) – necessary for calculating the volume needed/occupied in the cart
**W**: product width (cm) – necessary for calculating the volume needed/occupied in the cart
**H**: product height (cm) – necessary for calculating the volume needed/occupied in the cart
**M**: product weight – necessary for checking the content of a cart using the weighing sensor (scales)
**bQty**: the quantity in a box
**Qt**: the quantity that must be loaded into a cart
**batch**: product batch
**BL, BW, BH, BM**: sizes (length, width, height, weight) for a standard box of the respective product

Through this double checking system we ensure a maximum degree of error tolerance, and tote tracking in the industrial process of loading it onto the picking belt. Practically, should a certain type of tag be damaged (barcode or RFID tag) using redundancy ensures the tote is tracked in optimum conditions and implicitly the prediction and error analysis system generates inferences with maximum accuracy.

The basic objective of the innovation proposed by this study is the data inference (prediction) in "set 1” based on the data in "set 2”, or more precisely **predicting the times when the tote passes by**.

| pId | L | W | H | M | bQty | Qt | Lot | BL | BW | BH | BM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4913 | 56 | 56 | 141 | 306.4 | 24 | 5 | 491101A2 | 370 | 250 | 160 | 7818 |
| 5167 | 62 | 54 | 116 | 229.2 | 60 | 5 | FH1922 | 310 | 225 | 360 | 14022 |
| 18206 | 43 | 43 | 66 | 22.5 | 80 | 10 | 213133 | 350 | 220 | 145 | 1969 |
| 27843 | 67 | 54 | 186 | 251.12 | 36 | 5 | F1610 | 420 | 340 | 200 | 9355 |

**Fig. 13** The second data set, information related to the tote based on a given picking order

**Results of sub-experiment 1**

We take the square of the root mean square to be the reference error in the results analysis of the data prediction experiment. The data obtained is presented as a table containing the following information:
**ID**: observation identifier (the same as in data set 1)
**SensorID:** sole identifier of the sensor generating the observation (the same as in data set 1)
**Predicted Time (s):** time (with 3 decimals) predicted by the system for completing the respective segment of the industrial belt
**Real Time (s):** real completion time (the same as in data set 1)
**Squared error**: the squared error between the predicted and the observed time during a particular segment (for a certain observation)
**Root mean squared error**: the root of the square of the difference between the predicted and the observed time

| ID | SensorID | Predicted Time (s) | Real Time (s) | Squared error | Root mean squared error |
|---|---|---|---|---|---|

| ID | SenzorID | Timp Prezis (s) | Timp Real (s) | Eroare patratica (E) | Radacina erorii patratice ($E_{RMSE}$) |
|---|---|---|---|---|---|
| 1 | 4393724 | 0.000 | 0.000 | 0.0 | 0.000 |
| 2 | 4393731 | 63.746 | 61.294 | 6.0 | 2.452 |
| 3 | 4393747 | 147.690 | 139.330 | 69.9 | 8.360 |
| 4 | 4393761 | 78.013 | 76.483 | 2.3 | 1.530 |
| 5 | 4393767 | 16.927 | 16.927 | 0.0 | 0.000 |
| 6 | 4393788 | 95.756 | 88.663 | 50.3 | 7.093 |

**Fig. 14** Comparison between the real and predicted times

| ID | SensorID | Predicted Time (s) | Real Time (s) | Squared error | Root mean squared error | Acceptable error (10%) | Prediction error percentage (Ep) | Acceptable prediction (A) |
|---|---|---|---|---|---|---|---|---|

| ID | SenzorID | Timp Prezis (s) | Timp Real (s) | Eroare patratica | Radacina erorii patratice | Eroare accept. (10%) | Eroarea procen. a predictiei ($E_p$) | Predictie accept. ($A$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 4393724 | 0.000 | 0.000 | 0.0 | 0.000 | 0.000 | 0.0% | 1 |
| 2 | 4393731 | 63.746 | 61.294 | 6.0 | 2.452 | 6.129 | 4.0% | 1 |
| 3 | 4393747 | 147.690 | 139.330 | 69.9 | 8.360 | 13.933 | 6.0% | 1 |
| 4 | 4393761 | 78.013 | 76.483 | 2.3 | 1.530 | 7.648 | 2.0% | 1 |
| 5 | 4393767 | 16.927 | 16.927 | 0.0 | 0.000 | 1.693 | 0.0% | 1 |

**Fig. 15** Analysis of the system performance

We obtain thus the squared error: $ERMSE = 169.896\,\%$

By interpreting these primary data we notice that in most observed cases the root mean squared error is the **0-20% of the real observed value range for the time** required to complete a segment of the industrial belt (time generated by the sensor network for the respective section). Consequently we will consider **the acceptable error below 10%**:

$ET = Y * 0.1 \quad ; \quad ET = 48.753$

The obtained results are presented in table 4.5, including:

- **Value of the acceptable error** (*E*T): represented by 10% of the value of the observed time for a particular segment of the industrial belt
- **Prediction error percentage** (*E*P): represented by the ratio between the root mean squared error and the observed time for the respective segment:
- **Prediction acceptance indicator A**: is the acceptable prediction, and the indicator variable constituting the final element for the assessment of the proposed system. The {0,1} Boolean value of the indicator is **the most direct method for the measurement of the validity of the obtained prediction, for the times required for the tote to complete each segment of the industrial belt.**

Starting from the presented results we continued the analysis with the help of a series of indicators defined as follows: T=Number of observations with E:SE T = 12
F=Number of observations with E2:E T = 3
TR =T/(T+F)=12/(12+3)=0.8=80% (system accuracy)

As you can notice, we obtained an accurate prediction rate of 80% where, for 20% of the observed cases in the data sets analyzed, we had an error percentage (root mean squared error) of approximatively 14.0%, meaning 4.0% over the accepted threshold of 10%.

**If we increase the tolerance of the accepted error threshold ET from 10% to 15% we will obtain an accuracy TR = 100%,** according to the system performance analysis.
E_T=Y*0.15
E_T=73.12

| ID | SensorID | Predicted Time (s) | Real Time (s) | Squared error | Root mean squared error | Acceptable error (10%) | Prediction error percentage (Ep) | Acceptable prediction (A) |
|---|---|---|---|---|---|---|---|---|

| ID | SenzorID | Timp Prezis (s) | Timp Real (s) | Eroare patratica | Radacina erorii patratice | Eroare accept. (10%) | Eroarea procen. a predictiei ($E_p$) | Predictie accept. ($A$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 4393724 | 0.000 | 0.000 | 0.0 | 0.000 | 0.000 | 0.0% | 1 |
| 2 | 4393731 | 63.746 | 61.294 | 6.0 | 2.452 | 9.194 | 4.0% | 1 |
| 3 | 4393747 | 147.690 | 139.330 | 69.9 | 8.360 | 20.899 | 6.0% | 1 |
| 4 | 4393761 | 78.013 | 76.483 | 2.3 | 1.530 | 11.472 | 2.0% | 1 |
| 5 | 4393767 | 16.927 | 16.927 | 0.0 | 0.000 | 2.539 | 0.0% | 1 |

**Fig. 16** The consequences of increasing the error threshold from 10% la 15%

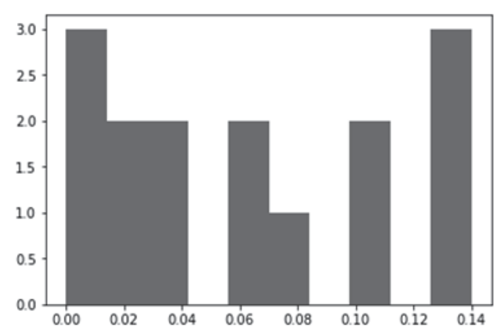



**Fig. 17** Error histogram *Ep*

The main element that is analyzed is the histogram of the “trust” in the innovative system proposed consisting of the observed values of the prediction error percentage (simple deviation from the observed value) *Ep*. As you can see in the histogram presented in Fig. 17, the proposed system generates an acceptable prediction error distribution, with a considerable quantity of inferences in the 0%-5% range.

As we stated in the beginning of the description of sub-experiment 1, we introduced a concrete error by intentionally damaging the tote barcode label and the analysis of the system operation. Therefore, the initial measurements together with the predictions shall be as presented in fig. 18. We chose to partially damage the tote barcode label in the industrial belt flow, after the reading performed by the optical sensor 4393795 (observation no 7).

As you can see, the readings performed at observations 8-15 will not generate information, and the acceptable prediction for all these readings will be null. Starting from the prerequisite of the analysis of the acceptable error percentage in the proposed range of maximum 10%-15%, we shall obtain errors over 100%, and the system shall enter alert mode implicitly, even after the first reading on the belt, made by optical sensor no 8 (4393805).

| ID | SensorID | Predicted Time (s) | Real Time (s) | Squared error | Root mean squared error | Acceptable error | Error percentage for prediction | Acceptable prediction |
|---|---|---|---|---|---|---|---|---|
| 5 | 4393767 | 16.927 | 16.927 | 0 | 0 | 1.693 | 0.00% | 1 |
| 6 | 4393788 | 95.756 | 88.663 | 50.3 | 7.093 | 8.866 | 8.00% | 1 |
| 7 | 4393795 | 96.714 | 84.837 | 141.1 | 11.877 | 8.484 | 14.00% | 0 |
| 8 | 4393805 | 69.26 | 0 | 4797 | 69.26 | 0 | 6926.00% | 0 |
| 9 | 4393809 | 26.419 | 0 | 698 | 26.419 | 0 | 2641.90% | 0 |
| 10 | 4393871 | 490.83 | 0 | 240914.1 | 490.83 | 0 | 49083.00% | 0 |
| 11 | 4393920 | 337.552 | 0 | 113941.1 | 337.552 | 0 | 33755.20% | 0 |

**Fig. 18** Results influenced by damaging the barcode label

**Results of sub-experiment 2**

In sub-experiment 1, after we damaged the label in the industrial belt process, the intelligent system proposed detected the error (the error percentage of reading 8 was of 6926%!) and alerted the human operator.

Although the process was blocked until this problem was remedied, this was not the optimum solution. As presented in the previous chapters, **the optimum solution is streamlining the entire process and minimizing blockage risks by doubling the optical sensors destined for totes with magnetic sensors.**

Going from the example above, with 15 observations and 15 predictions respectively, to **analyzing a large volume of data**, we assessed the evolution of the entire experiment and the behavior of the *ERMSE* error. It is important to specify that in this sub-experiment 2 we **added, apart from optical sensors (marked by "O" in our observations) the magnetic sensors proposed in the architecture of the experiment (marked by "M" in our observations)**. The obtained results are presented in Fig. 19.

| D | SensorID | Type | Time | Predicted time | TimeDelta | Squared error | Root mean squared error | Acceptable error | Prediction error percentage | Acceptable prediction |
|---|---|---|---|---|---|---|---|---|---|---|

| ID | SenzorID | Tip | Time | Timp Prezis | Time Delta | Eroare patr. | Radacina erorii patratice | Eroare accept. | Eroarea proc. a predict. | Predictie accept. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4881554 | M | 2016-05-10 09:21:46 | 0.00 | 0.00 | 0.0 | 0.000 | 0.000 | 0.0% | 1 |
| 2 | 4881558 | O | 2016-05-10 09:22:20 | 31.02 | 33.71 | 7.3 | 2.697 | 3.371 | 8.0% | 1 |
| 3 | 4881559 | M | 2016-05-10 09:22:31 | 12.46 | 11.54 | 0.9 | 0.923 | 1.154 | 8.0% | 1 |
| 4 | 4881562 | O | 2016-05-10 09:24:17 | 99.03 | 105.35 | 40.0 | 6.321 | 10.535 | 6.0% | 1 |
| 5 | 4881563 | O | 2016-05-10 09:24:34 | 16.11 | 17.51 | 2.0 | 1.401 | 1.751 | 8.0% | 1 |

**Fig. 19** The results obtained with the dual system of optical (O) and magnetic (M) sensors

As you can see in fig. 19, **the innovative system proposed registered in this experiment with 122**

**observations (measurements made by sensors) an average accuracy of 88.52%.**

The next logical step in sub-experiment 2 is obviously **damaging the barcode label (starting with the tote route between points 15 and 16 on the industrial belt) and we let the system auto-adapt by using the dual magneto-optical sensor network**. Thus, the primary data collected by the system and initially predicted are presented in fig. 20, with the mention that, for the reduction of the volume of data presented, we will analyze only observations 13-31.

| ID | SensorID | SensorType | Time | Predicted time | TimeDelta | Squared error | Root mean squared error | Acceptable error | Prediction error percentage | Acceptable prediction |
|---|---|---|---|---|---|---|---|---|---|---|

| **ID** | **SenzorID** | **Tip Senzor** | | **Time** | **Timp Prezis** | **Time Delta** | **Eroare patrat.** | **Radacina erorii patratice** | **Eroare accept.** | **Eroarea proc. a predictiei** | **Predictie accept.** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 4881606 | 10457 | O | 2016-05-10 09:35:26 | 25.49 | 24.05 | 2.1 | 1.443 | 2.405 | 6.0% | 1 |
| 14 | 4881619 | 2225 | M | 2016-05-10 09:37:21 | 116.98 | 114.68 | 5.3 | 2.294 | 11.468 | 2.0% | 1 |
| 15 | 4881628 | 10457 | O | 2016-05-10 09:39:32 | 123.93 | 131.84 | 62.6 | 7.911 | 13.184 | 6.0% | 0 |
| 16 | 4881631 | 7383 | O | 2016-05-10 09:40:39 | 61.12 | 0.00 | 3735.1 | 61.116 | 0.000 | 6111.6% | 0 |
| 29 | 4881685 | 7487 | O | 2016-05-10 10:05:00 | 0.00 | 0.00 | 0.0 | 0.000 | 0.000 | 0.0% | 1 |
| 30 | 4881688 | 13160 | O | 2016-05-10 10:06:13 | 0.00 | 0.00 | 0.0 | 0.000 | 0.000 | 0.0% | 1 |
| 31 | 4881690 | 7421 | M | 2016-05-10 10:07:54 | 254.26 | 244.48 | 95.6 | 9.779 | 24.448 | 4.0% | 1 |

**Fig. 20** Results obtained with the dual sensor system (O-M) and the damaged barcode label

| **Test** | **No of observations** | **Inference error percentage (A)** |
|---|---|---|

| **Test** | **Numar de observatii** | **Eroare procentuala de inferenta (A)** |
|---|---|---|
| 1 | 15 | 80% |
| 2 | 100 | 81% |
| 3 | 150 | 82% |
| 4 | 200 | 83% |
| 5 | 300 | 84% |
| 6 | 500 | 85% |
| 7 | 1000 | 87% |
| 8 | 1500 | 89% |
| 9 | 5000 | 90% |
| 10 | 6000 | 90% |
| 11 | 10000 | 91% |
| 12 | 50000 | 92% |
| 13 | 100000 | 92% |
| 14 | 250000 | 93% |
| 15 | 500000 | 93% |
| 16 | 1500000 | 93% |

**Fig. 21** The variation of the system's accuracy over time

As can be observed from the lines related to the observations 16 and 19, generated by two approximately successive reading performed with optical sensors, the percentage error of the predictions far exceeds 100%. **In this case, the system shall begin with the reading 20 and shall use exclusively magnetic sensors, without taking into consideration optical readings**. Therefore, the system shall finally function without interruptions and shall virtually attain the same prediction rate for the monitoring of the process, even in the event of malfunctioning/deterioration of the barcode label. In this case, **the total decrease of the accuracy percentage is less than 1% from 88.52% to 87.70%.**

***Conclusions regarding the scalability of the suggested system***

Following the two sub-experiments, the variation of the system's accuracy over time, given by the error *E*, depending on the data volume processed by the system is in accordance with table 4.10. The graphical representation from Fig. 22, using liniar or logarithmic scale, highlights the expected phenomenon - **over time and after observing an ever-rising quantity of data, the percentage error for inferences *A* decreases more and more and the interval for reliability becomes narrower**.

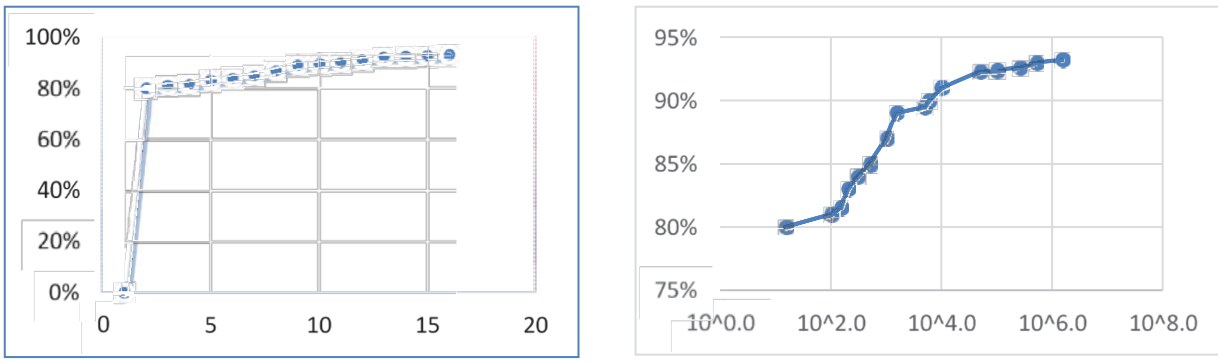



**Fig. 22** Evolution of accuracy depending on the number of processed observations, using the liniar scale (left) or the logarithmic scale (right).

As can be observed, the percentage error for inferences (*A*) has an asymptotic evolution towards a maximum value of 94% for the percentage error for inferences**. The system reaches optimum efficiency when a minimum number of *104* observations generated by the dual sensor network of the industrial conveyor belt** are processed. After this set of analyzed data (104 - 105), the system stabilizes in an area with relatively small improvements.

The experiment has proven that the improvements made contribute decisively to the continuous self-adaptation of the system to unforeseen or "rare" factors arising during the industrial process.

## CONTRIBUTIONS AND ORIGINAL RESULTS

The original contributions made **by this thesis answer some real needs highlighted through the analysis of a warehouse for pharmaceuticals, from Bucharest**. A part of the solutions that were discovered have already been implemented, leading to an improvement of the industrial process. The PhD programme covered the analysis, research and design stages with a focus on the development stage.

**The subject of the thesis belongs to a multidisciplinary subject, in which Electrical Engineering elements are integrated in a highly complex (technical and IT) system**, which requires an adequate modeling of the breakdown of the integrated distribution system into interconnected subsystems.

For a practical analysis of the contribution and applicability of the presented study, we shall make a direct analysis of the practical aspects that have been pursued in the analysis, research and design stage, but especially in the experimental development stage.

Practically, through the decision to implement the experiment in a real execution/production environment - namely in a warehouse for pharmaceuticals - a real analysis process was generated and a significant number of deficiencies in the industrial order management system were observed, from the placement of an order and up to the shipment of the order (specified in the detailed description of the experiment):

1. **The need/lack of capacity to analyze the impact of the intervention of the human operator on the industrial conveyor belt** - the lack of a correlation between the operator processing the order and the processing tote makes tracking the emergence of an error during processing much more difficult;

2. **The need/lack of capability to validate primary verifications performed on the industrial conveyor belt** - the existence of a single method to check the integrity of a processed order (the weighing method);

3. **The need/lack of a self-adaptive method for a predictive estimation of the industrial processes** - the existence of a single method for tracking the tote on the conveyor belt by means of a barcode (subject to constant and sometimes accelerated deterioration) and an optical reading unit (which can malfunction).

**In order to study the functioning of a warehouse for pharmaceuticals, research cannot be approached purely from an analytical viewpoint, without gaining knowledge and understanding of the whole system.** First of all, the behavior of a highly complex system is important. Secondly, feedback from the systems is an essential element in order to understand the behavior of the systems. For the dynamic modeling of the system, a holistic control paradigm must organize scientific methods but may also use the results of analytical research to define the static relationships between the variables in a modeling procedure allowing the simulation of the system's dynamics as part of the study.

The progressive advancement compared to the actual state of industrial systems for warehouses for pharmaceuticals was achieved using the following strategy:

A. **The holistic management of industrial processes,** thus allowing the application of multiple modern paradigms, as well as the usage of semantic data and knowledge-based management.

**B.** Combining the actual state of technology in the field of **iWSN with advanced industrial optimization methods based on Artificial Intelligence.**

C. I**mplementation of technical solutions that will solve the deficiencies of current systems**, deficiencies that were previously mentioned.

D. **Introduction of self-evolving algorithms**, especially by optimizing and implementing convolutional deep neural networks within the architectures of industrial systems and the systems for the management of industrial processes.

E. Research and development of a **massive parallel processing infrastructure** that will allow real-time support from Artificial Intelligence agents.

The quantifiable objectives and the original results obtained can be described as follows:

1. ***The original research of a self-evolving industrial system for picking and replenishment for automated and semi-automated entities, which bring a new approach in the management of warehouses for wholesale, based on self-evolving semantics with a constant adaptation to the ever-changing environment.***

   The practical applicability is immediate in the case of complex warehouses for pharmaceuticals, with special features: product traceability, expiry date, express delivery, international distribution standards, and high quantities for many different products.

   This study aims to change the way automated warehouse systems are programmed and this becomes an important issue for all large warehouses, were emphasis is placed on the optimization of costs for the whole value chain. Industrial automation requires a holistic approach in order to rise to such future challenges and this research is an important step towards achieving this goal. The holistic approach considers that there is a possible difference in quality between the entire system and its components. Modularization or the analytic approach may fail and therefore the holistic approach shall ensure the closest resemblance to the real industrial process. This holistic approach of optimizing complex warehouses for pharmaceuticals as well as the result of this research shall create innovative and original models and concepts.

   In the automated warehouse management process, because the flow of merchandise is constantly changing with each customer order and because the flow is correlated with changes in the internal and external environment this may lead to an increase of the time required for accepting, packaging and preparing the delivery and the storage space may become inadequate and the storage must be relocated to improve the management of the merchandise and to reduce storage management costs.

   **<u>The original result</u> is the functional experimental system based on which the predictive automation experiment shown in Chapter 4 of the thesis was generated.**

2. ***The comparative study for an extended range of sensors (magnetic and optical) for the purpose of determining the sensors that may supply correct values to the system, regarding the factors critical to the functioning of the picking line for a warehouse for pharmaceuticals.*** The automation of activities takes into account international standards (GDP/GMP – Good Distribution/Manufacturing Practice) specific for the pharmaceutical industry, where product traceability is a critical requirement for systems.

   Following this study, the use of a dual sensor (magnetic and optical) systems was suggested that would allow real-time monitoring and management of the warehouse for pharmaceuticals, which would lead to a significant decrease of errors caused by input parameters and which would allow the system to adapt quickly to unusual situations that may arise during the operation of picking the drugs.

   In order to ensure the validation of the tote's content, especially in the case of very expensive products, magnetic tags made of nanocrystal/amorphous alloys, rich in Co, spread out in thin layers, which lead to an extremely precise reaction concerning the existence of the products thus verified in the tote, the measurement error being lower than 0.01%. Another role of these tags is to protect the unit against unauthorized tampering with the drugs, an essential rule for the authorization according to international good practice standards.

   **<u>The original result</u> consists in the analysis, development and experimental testing of the dual sensor network suggested in Chapter 4. For the magnetic tags, several magnetic materials in thin layers were studied and were proven to be reliable in the industrial pharmaceutical environment and ensured the identification of the tote's position at the control points. The introduction of**

**sensors and magnetic tags lead to a significant decrease in the number of errors, ensuring a better real-time reaction of the system to perturbation factors.**

3. ***The creation of a feasibility study for Mediplus Exim in order to implement a complex architecture consisting of sensors and transducers connected via a "fog computing" network, with big-data capabilities, with predictive analysis based on advance artificial intelligence models, combining the latest innovations in this field.***

For the particular case of the industrial pharmaceutical process for picking (warehouse storage etc.), the applicability of "fog computing" refers to the proposal to use intelligent wireless sensors with own information storage and processing capabilities. These "node" sensors have the ability to take over a sizeable part of the computing requirements of the whole system and thus become an acquisition node and a computing node for "fog computing". For the automated centralization and processing of information a "cloud computing" environment based on Microsoft Azure resources is used.

The sensors tested and placed in the warehouse have internal communication routing capabilities, becoming routers if needed (one of the devices is not within the range of a router, but is in the proximity of another device which falls within the range of another router).

**<u>The original result</u> consists of the design of an iWSN network, for the supplier Mediplus Exim, allowing the reception of the signal from any point inside the warehouse. This configuration (mesh network) has a relatively low error rate compared to a classic star topology (with a single router and sensors without routing capabilities). The coverage range is extended allowing for more communication paths for the gathered information (enhanced redundancy).**

4. ***The elaboration of an artificial intelligence model based on "deep learning" and network sensors for the management of industrial planning and logistics, according to the particular characteristics for a warehouse for drug distribution.***

An innovative architectural approach for self-evolution (genetic) algorithms, based on libraries for semantic knowledge was established. The result was shown in an architectural report whose purpose is the complete description of the methodology suggested for self-evolution (genetic) algorithms, using the object modeling approach [3]. New evolutionary algorithms shall create a basis for the development of a new generation of warehouse automation systems and processes.

Special attention was given to the class of self-evolution algorithms governing product picking. A model simulating the operation was created based on a deep neural network and the modeling of the elements and processes of a warehouse for pharmaceuticals was performed. Against this background, the concepts underpinning the development of software applications that shall control the warehouse activities, but also the methods used by the self-evolution industrial algorithm for picking were presented [4] [5].

Innovative software was created, which applies industrial self-evolution algorithms for serialization and picking. The same approach was used for the replenishment process for the warehouse for pharmaceuticals.

**<u>The original result</u> consists of the neural network software created and presented in Annex 2. We observe the prediction rate of over 90% for the suggested system, under the conditions of assuming a maximum tolerance of 5-10%.**

5. ***The elaboration of a volumetry algorithm, integrated in the ERP/WMS system, which ensures the optimum distribution of totes in the loading stations for pharmaceutical products,*** thus ensuring a constant work flow on the conveyor belt and which, in correlation with the information supplied by the predictive network, increases the productivity of the entire system, ensuring better transparency with respect to the time required for the delivery to the customers and of the volume that can be processed in a given unit of time.

   **<u>The original result</u> consists of the software module integrated in the general warehouse management system, inserting the modifications brought by the presence of magnetic tags spread out in thin layers, elements which improve the management of the movements and of the loading of totes, including in emergency situations (absence of a label). The experiments suggested in Chapter 4 showcase the reliability and the efficiency of the suggested solution.**

6. ***The identification of directions for extending research and the area of applicability, taking into account the existence of similarities with any other automated warehouses.*** What sets this study apart from different approaches are the particular requirements of the pharmaceutical industry: picking products according to the expiry date, traceability based on manufacturing batches, serialization of the products (barcode on the delivered unit, according to European directives).

The original results obtained as well as the technologies used demonstrate significant and innovative improvements in many areas.

The suggested system allows the serialization of unique articles, of packages, boxes and pallets during the picking of the products. With traceability ensured for each element, the transparency of the whole process ensures a high level of security, required for the distribution of pharmaceutical products. The system offers the monitoring of the products until the sale using defined distribution channels, as well as compliance with European and/or national legal requirements.

The suggested system ensures the distribution of a wide range of high-value pharmaceutical products and poses special challenges. The very high expectations from customers (pharmacies, hospitals and so on) regarding the delivery time and quality place great pressure on the operation of the warehouse. A reliable distribution system for customers and adaptation to strict regulatory requirements are essential. The warehouse processes must be continuously optimized.

This complex and ever-changing activity was significantly improved by **implementing self-evolution automation systems and processes, both in the warehouse control system, as well as in the warehouse management system**. This research advances a model with several objectives, using self-evolution semantics, based on evolutionary algorithms in order to solve the model determined by the characteristics of warehouses for pharmaceutical products and the characteristics of automated warehouses. Thus, the efficiency of the movements of pharmaceutical products in the warehouse but also from the warehouse to the customers, the storage of the products, the transport time and the costs of product movements shall improve.

By **creating a model simulating the warehouse for pharmaceuticals**, based on agents, we have followed the evolution of the processes for selecting and processing orders that will form the base for the programming of all resources required for the performance of the product picking activity (workforce, equipment, warehouse design). The order selection operations often make up a large part of the total number of warehouse activities (even 60% [19]) and for a normal warehouse the selection of orders can make up 55% of the total operating costs. This is one of the most important objectives when trying to reduce the operational costs and the workforce required in warehouses.

The preliminary results obtained may have a significant impact, because by using self-evolution semantics, based on evolutionary algorithms, **a total cost optimization greater than 20%** can be achieved by optimizing the flows, reducing the time, increasing the speed of operations and by avoiding delays.

## ESTIMATED IMPACT

The result of this study from this thesis consists in creating a model with multiple objectives, using self-evolution semantics, based on evolutionary/genetic algorithms and creating a concept-model, than can be further used to create an expert system for warehouses in the near future. There are many market opportunities and an **expert system for the management of warehouses for pharmaceuticals** has a real commercial potential, because **it can optimize the total costs with more than 20%**, by optimizing flows, reducing processing times, increasing the speed of operations and avoiding delays.

This warehouse system for pharmaceuticals ensures the distribution of a wide range of high-value pharmaceutical products and poses special challenges. The very high expectations from customers regarding the delivery time and quality put great pressure on the operation of the warehouse. The suggested improvements refer to the reliability and the speed of distribution to the customers as well as to the observance of strict regulatory requirements, requirements which are vital. The warehouse processes must be continuously optimized, and by using the results of this research, this objective can be permanently achieved.

This study shall also create the premises for **the development of an integrated expert warehouse management system** in order to improve the current warehouse control system, by integrating with the ERP system which manages, optimizes and streamlines the internal business processes for companies from the industry for the distribution and sale of pharmaceutical products. **It is a specially designed multi-module system which can offer support to all the business sectors of a company** by standardizing the decision-making processes or the production processes and by introducing the good practice found in the retail and wholesale pharmaceutical sector as well as in other sectors. The possible partners could be the biggest wholesalers on the pharmaceutical market, which have the best coverage of the chain (manufacturer-wholesaler-pharmacies-customers).

## PERSPECTIVES FOR SUBSEQUENT DEVELOPMENT

The thesis contains the elements required for the subsequent development in four directions, with a maximum degree of innovation (we don't know of the existence of similar products on the market as of this moment):

1. **The introduction of a new element for the optimization of the industrial process by visual/optical inspection of the totes' content.**

This direction is a practical one, with immediate industrial applications in the field of industrial warehousing and automated warehouse management. If the process is optimized using visual recognition and inspection, we are dealing with the introduction of a new assembly in the suggested system. This new subsystem has the following components and functions:

- The subsystem contains an industrial surveillance camera placed above the industrial conveyor belt, camera which (at certain control points) takes pictures of the content of the totes and send the images for real-time analysis to be performed.
- the second component of the subsystem is an integrated parallel computing device for industrial

environments (for instance NVidia Jetson NX1, NX2) which performs a real-time analysis of the image sent by the industrial surveillance camera and decides on the conformity of the tote's content with the associated order.

- In order to make the process more efficient, this subsystem is connected and coordinated by the main system proposed in this paper and demonstrated in Chapter 4.

- The prediction system for the execution/loading of totes shall signal to the inspection subsystem with visual recognition the situation in which a tote did not travel the route in the estimated time, thus replacing a human operator who would have been usually obligated to check the potential "alarm" generated by the predictive system.

**2. Manufacturing an electronic device with integrated neural network.**

The design of an electronic device featuring an artificial neural network coded at the level of logical electronic circuits is intended. The idea of an circuit embedded in the neural network ("*circuit embedded artificial neural network*") is a concept which, at this time, involves research and development activities and has applications at the level of electronic devices for "*consumers*", being used in its basic, simple forms in applications such as the identification of license plate numbers ("*automatic name plate recognition*") and in other similar visual recognition applications. These applications use simple neural network models entirely connected, without applying in the design of the electronic circuit models based on the actual state of research and technology, in other words, without using convolutional neural networks.

This possible extension is based on the idea of designing an electronic circuit which embeds the structure of a convolutional neural network previously pre-trained in an experimental environment. The device designed as such shall be capable to generate inferences based on different configurable structures with electrical input signals. Obviously, the idea of this device's self-improvement (generic improvement in our case) is also pursued by adding a "*flash*" memory, where the coefficients of the self-evolution model for the embedded circuit are stored. With respect to hardware implementation, we can opt for a SoC (System on Chip) which contains a processor for the operating system and for handling raw data and an FPGA (Field Programmable Gate Array) structure for the neural network model, thus resulting in the acceleration of information processing and reducing processing latencies.

3. **The implementation of predictive algorithms for the automation of forecast and replenishment processes,** in permanent correlation with the stocks required for the continuous delivery of customer orders (pharmacies, hospitals, medical clinics) and corroborated with the estimated delivery times assumed by drug manufacturers.

**4. Designing an assembly consisting of a sensor and an intelligent actuator, with automated learning models, based on the concept of electronic devices with embedded neural networks.**

The intelligent sensor nodes from modern industrial sensor-transducer-actuator networks usually perform simple operations such as picking, temporary storage, weighting and transmission of telemetry information. Although these nodes fall in the category of "fog computing" systems, their capacity of "thinking" and becoming involved in the effective decision-making process is severely limited. By developing a sensor prototype which includes the element of the electronically embedded (convolutional) deep neural network, this sensor becomes truly intelligent thus obtaining the capacity of making complex decisions and the capacity to self-adapt, both at individual level, as well as at the level of the entire sensor network infrastructure [13].

The suggested intelligent sensor must be capable to self-adapt and self-model the weightings of the coefficients from its neural electronic network (by using the Flash memory) and to transmit to neighboring nodes from the sensor network (iWSN) the modifications made in its embedded structure of its own convolutional neural network (CNN).

Considering the current technological state with respect to processing power in mobile devices (inversely proportional to the electrical power needed to perform these calculations), the integration of an NVIDIA Jetson TX2 module can be studied, together with the characteristic circuits of the classic sensor, in order to add to the latter the capabilities of the neural network as well as the capabilities of the decision-making component, without considerably sacrificing the capacity of this device, compared to a classic device, with no processing power.

The characteristics that make it suitable for this application are specified below:

- GPU NVIDIA Pascal, 256 CUDA cores
- CPU with 6 cores, 2 with Denver architecture, 4 with ARM A57 architecture
- 8GB RAM DDR4
- interface support for up to 6 video cameras and 4 screens
- 32GB storage space
- WiFi, Bluetooth connectivity, but also CAN, UART and SPI connectivity for sensors.

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