POLITEHNICA UNIVERSITY OF BUCHAREST

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PH.D.
THESIS
SUMMARY

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CONTRIBUȚII PRIVIND ÎMBUNĂTĂȚIREA PRACTICILOR ÎN INDUSTRIA 4.0

CONTRIBUTIONS ON IMPROVING PRACTICES IN INDUSTRY 4.0

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Chapter 1

Introduction

1.1 Presentation of the field of the doctoral thesis

The fourth industrial revolution, also known as Industry 4.0, is currently underway. The first industrial revolution took place in the second half of the 18th century with the widespread adoption of mechanisation and the steam engine. The second industrial revolution began towards the end of the 19th century with the popularisation of the assembly line for mass production. This period is characterised by the production of steel and chemicals, the introduction of the internal combustion engine instead of the steam engine and the discovery of electricity. The third revolution began in the 1970s with the use of programmable systems and industrial robots to automate mass production processes, leading to an increase in productivity.

The objectives of the changes proposed by Industry 4.0 are to achieve adaptability, predictability and reliability of the entire industrial and business process. These goals can be achieved by using a variety of technologies such as machine learning, artificial intelligence, the internet of things or advanced data analytics.

1.2 Scope of the doctoral thesis

Through the research work in this PhD programme I have investigated specific problems and identified solutions to the challenges of Industry 4.0 which aims to create a network for vertical connection between sales, design teams, production machinery, raw material suppliers, assembly teams and customer support. Among the known issues I investigated are:

- Poor monitoring of electricity consumption in industrial environments [23].
- Data transmission standards are insufficiently secure and there is a risk of malicious interference.
- Lack of supporting IT systems allowing production to be adapted to customer requirements.

- Poor or unstructured recording of information makes it impossible to generate reports or statements to help planning and management processes.

This PhD thesis brings contributions to improving practices in Industry 4.0 through technologies such as Internet of Things (IoT) and Internet of Services (IoS).

1.3 Content of the doctoral thesis

This paper deals with theoretical and practical elements of Industry 4.0, presents experimental results and ways of implementation in the particular case of a company doing custom furniture manufacturing and interior design. The rest of the thesis is structured in eight chapters as follows:

- Chapter 2, entitled **Current state of research in Industry 4.0**, presents a summary of the technologies used in the context of Industry 4.0 information systems.
- Chapter 3, entitled **Monitoring raw material sources**, deals with the issue of monitoring forests as a direct source of raw material in the production chain.
- Chapter 4, entitled **Electricity in Industry 4.0 systems**, addresses the subject of energy consumption in a modern factory.
- Chapter 5, entitled **Quality assurance in composite manufacturing**, presents a component of an Industry 4.0 IT system for quality assurance in the production area.
- Chapter 6, entitled **Just-in-time co-ordination in Industry 4.0 processes**, traces concepts introduced as early as 1982 in Toyota factories in Japan with the aim of reducing waste throughout the production flow. It shows how these principles can be adapted to modern factories and improve results by taking advantage of technological advances in digital information systems and computer networks.
- Chapter 7, entitled **Systems Reliability in Industry 4.0**, deals with the topic of manufacturing systems reliability.
- Chapter 8, entitled **Digital twin in Industry 4.0**, presents how to integrate all the components presented in the previous chapters or introduced in this chapter itself, in order to achieve a unified digital representation of the entire operational process in the enterprise.
- Chapter 9, entitled **Conclusions**, highlights the results of the research work in the PhD programme and the author’s original contributions.

Chapter 2

Current state of research in Industry 4.0

2.1 Analysis of the state of the art in Industry 4.0

The fourth industrial revolution represents a connected but decentralised set of service providers and service consumers within a factory, vertically and horizontally integrated to align with manufacturing business processes and the entire supply chain [1].

Sensor networks are currently used in various configurations, wired or wireless, with monitoring or also actuation, stand-alone or connected to Industry 4.0. Applications include composite manufacturing [8], electric grid monitoring [4, 6], agriculture [26], smart homes [17], smart city [20] etc.

Sensor-Cloud Systems and Applications (SCSA) are also widely used. A novel approach to environmental monitoring and management combines IoT, Cloud Computing, Geoinformatics, Remote Sensing (RS), Geographic Information System (GIS), Global Positioning System (GPS) and e-Science for environmental monitoring and management. A case study on regional climate change and its ecological effects is presented in [10].

Virtual representation and modelling play a significant role in a consistent description and assessment of the SCSA. The use of a central cloud controller can lead to improved sensor availability and data reliability in remote monitoring. The use of a data verification function based on all sensors in an area offers three main advantages: fault detection, fault masking, energy management [21].

The cloud part of SCSA is also a major contributor to the reliability of the whole system. An increasing number of Cyber-Physical Systems (CPS) have been deployed in cloud platforms, and to host numerous CPS applications, cloud data centres are often composed of a huge number of physical compute and storage nodes, and the number of them is constantly increasing [24]. Virtual Machine (VM) management and scheduling plays an important role in providing a reliable service to the end-user while optimizing energy and resource usage [19].

The security of these distributed systems relies on the authentication of any entity entering or accessing data in the cloud. Authenticating the data exchange partner while maintaining confidentiality poses a new problem for SCSA. Some user authentication protocols for WSNs have been proposed to address this problem [12].

Reliability and maintainability play an important role in the safe operation of a production line. The topic of manufacturing process optimization is also considered from a holistic perspective by replaying the optimization action whenever necessary, i.e. every time new decisions need to be made.

The theme of Industry 4.0 systems also covers working methods in the context of warehouses. In [13] the methods and concepts needed to achieve a holistic approach to the maturity of warehouse operations by creating the ergonomic maturity model are described in detail.

2.2 Conclusions of chapter 2

Over the course of my doctoral studies I analysed over 100 references (articles, books, web pages) in order to document the situation in the field at the time. The critical analysis of the bibliography shows various limited approaches in the field of Industry 4.0, which bring improvements on a narrow topic but are unable to work together in an integrated system to realise the true potential of the proposed concept of the fourth industrial revolution.

In the scientific research carried out, I paid attention to the concept of integrating multiple technologies and systems in the ecosystem. I have designed an architecture based on microservices and worked on several microservices topics with specific applicability in the custom furniture production chain, such as: sensor networks, sensor-cloud systems and applications, SCADA systems, use of cloud in industry, supply chains, big data handling, digital twin, automated communication between stages of production processes, Computer Aided Design (CAD) systems, Computer-Aided Manufacturing (CAM) systems. Studies on reliability, maintainability and security in industrial environments in the literature are not adapted to the new technologies of the digital information age, therefore I have dedicated a chapter of the thesis to these issues in the context of a microservices information system integrating IoT and IoS technologies.

Chapter 3

Monitoring raw material sources

This chapter presents an expert system that I designed and tested for telemetry forest environment monitoring applications. The system includes sensor hubs and a central cloud server with multiple capabilities. I present a new approach using LIDAR sensors placed at ground level to obtain useful data from the forest environment.

3.1 Theoretical considerations on monitoring raw material sources

Sustainable forestry, or sustainable forest management, is the practice of managing forests to meet society's current needs from forest resources, without compromising their availability for future generations. The new understanding of the benefits of forests in highly developed countries, such as reducing carbon dioxide emissions to the atmosphere, water production, wildlife habitats, landscapes, recreation and other values, is of greater social interest than commercial timber production [2].

3.2 Experimental model for monitoring raw material sources

I designed an expert system to monitor activities in forest areas. The system has two main components: remote sensing hubs and a central cloud. There can be multiple sensing devices spread over an area of interest, each connected wirelessly via the internet to the central hub. The central server is responsible for authenticating and authorising devices to send data, receiving and storing data, making data available to users via a web interface and email alerts. The experimental device of the sensing hub is shown in Figure 3.1.

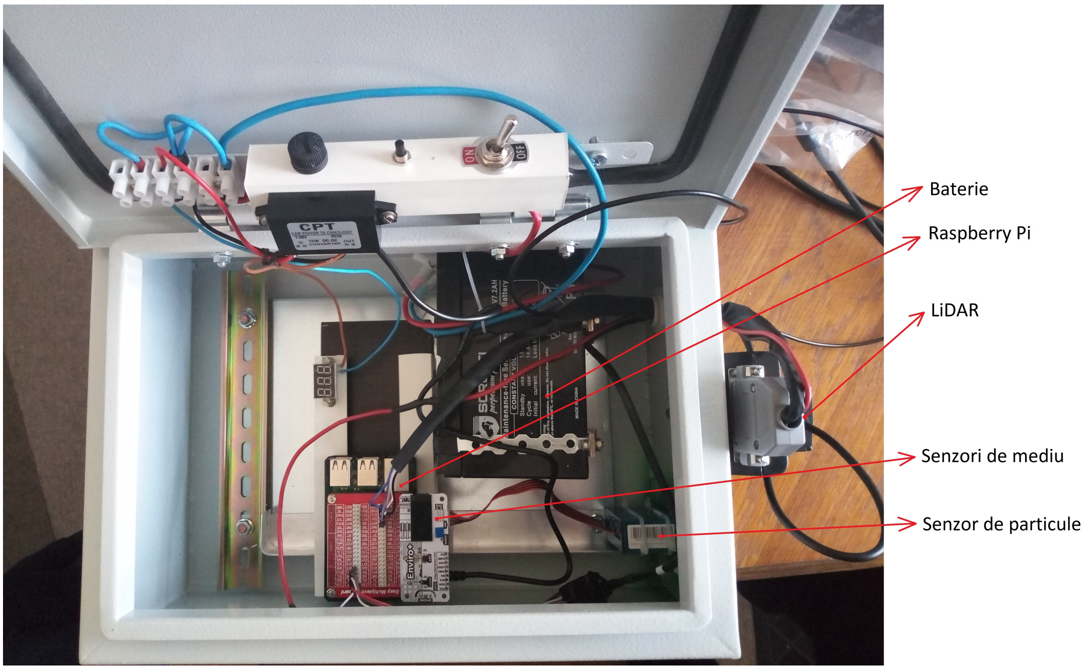

Fig. 3.1 Experimental model of the detection component [14].

3.3 Experimental testing of the forest monitoring system and results

To evaluate the effectiveness of the expert system, a remote sensing hub was installed near the edge of a forest. By placing objects between the sensor hub and trees, we confirmed that LIDAR was able to detect foreign objects, and the central hub of the expert system generated alerts. Figure 3.16 shows the baseline measurement in blue and the current measurement in orange. There are successfully identified foreign objects based on the median of the baseline and the current reading.

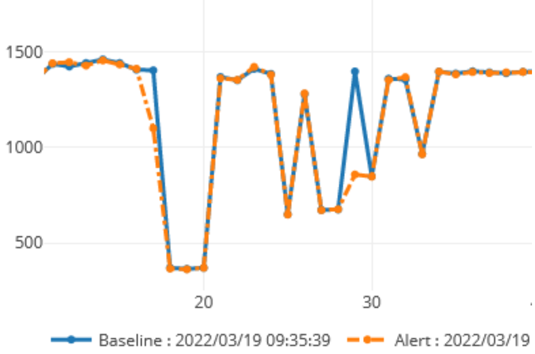

Fig. 3.16 Foreign object alert.

On the server side, the presentation of acquired LIDAR data from the test site can be seen in the web interface as shown in Figure 3.17.

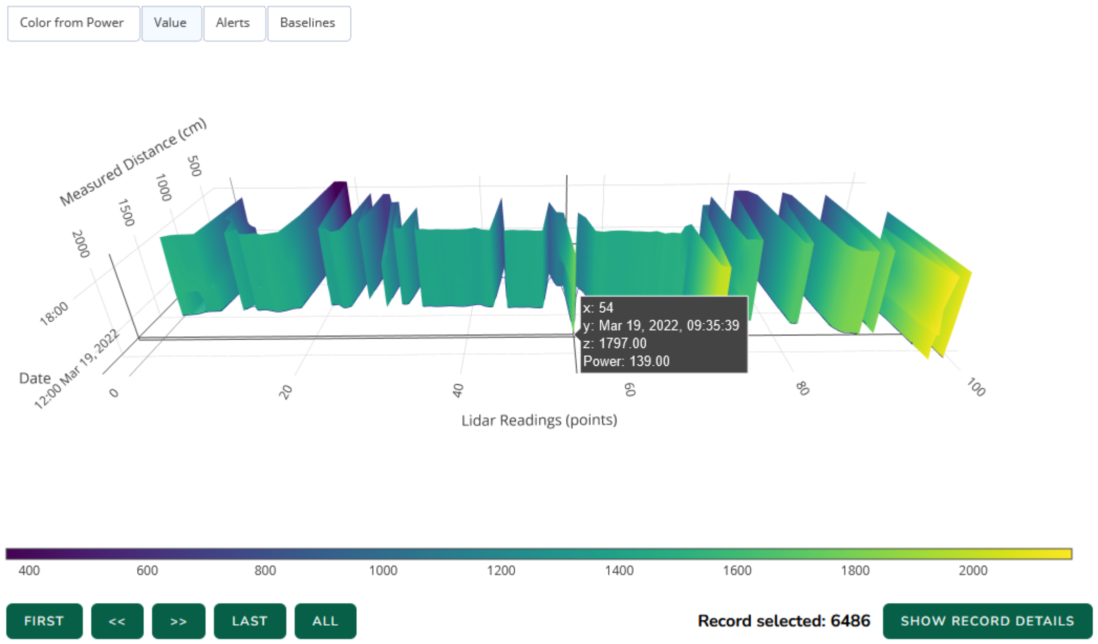

Fig. 3.17 Viewing LIDAR sensor data in the web interface.

3.4 Conclusions of chapter 3

Short reaction time to critical events is very important. The system I have developed has proven to be effective in identifying abnormal situations and sending alerts to users registered in the web application. In addition, real-time knowledge of conditions in the forest helps to increase the safety of people responding to crisis situations.

The personal and original contributions consist in the realization of the expert system architecture, the implementation of software components, the integration of components, the use of LIDAR sensors as a viable data source in forest environments, the optimisation of the system for sending alerts in less than one minute, the creation of services and programmable interfaces for integration into the overall Industry 4.0 system.

The research results presented in this chapter have been disseminated in other articles in the literature. The paper entitled *Evaluation of the Use of LIDAR Type Systems in Environmental Protection* was published in *2022 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR)* [14]. The paper entitled *Ground level LIDAR as a contributing indicator in an environmental protection application* has been submitted for publication in the journal *Expert Systems with Applications*.

Chapter 4

Electricity in Industry 4.0 systems

The activities presented in this chapter support the efforts to integrate smart grid technologies into an Industry 4.0 information system, with contributions to adapting existing smart metering technologies to industrial requirements. I focused on data security and accessibility, using transmission encryption and special web technologies tailored for the purpose of the project.

4.1 Theoretical considerations on the smart grid

Figure 4.5 shows the main components of the cloud subsystem. The communication module accepts incoming connections from remote, distributed smart metering units and is responsible for maintaining the socket, authenticating the client and authorizing access to data storage and commands. The interface generation module is responsible for preparing the view to display data at the appropriate scale and ratio of the web interface screen.

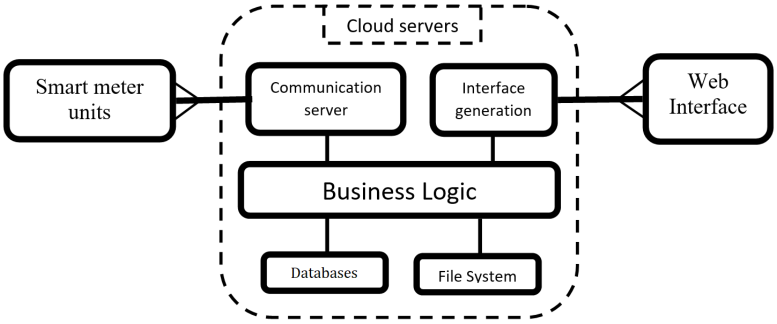

Fig. 4.5 Cloud subsystem diagram [4].

4.2 Grid monitoring system

The system records several electricity parameters every minute. The graph allows users to zoom in or out on the horizontal axis to achieve visibility at the desired granularity. One such example is shown in Figure 4.7.

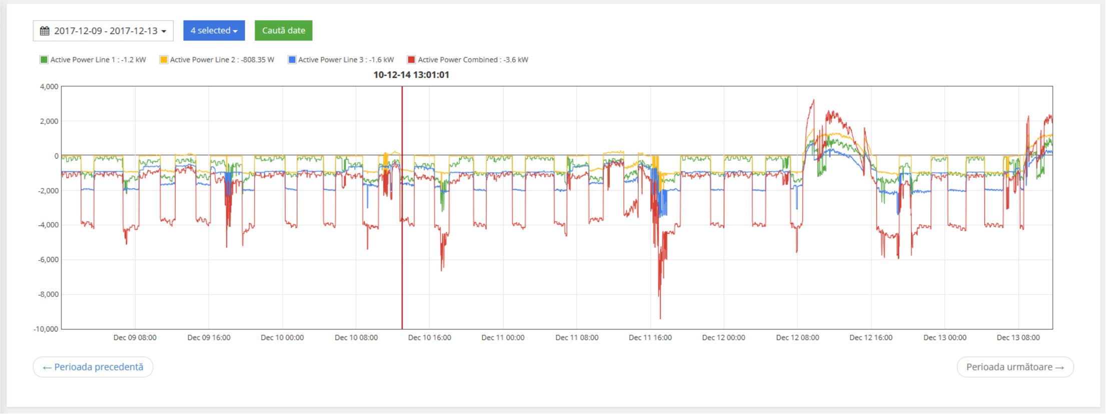

Fig. 4.7 Line chart of historical data [4].

The system can monitor multiple meters, depending on the requirements of each implementation. The data recorded from each zone or consumer can then be used to consolidate and validate information entered from other sources in the Industry 4.0 environment. Such use cases include machine uptime, employee time, energy consumption and costs.

4.3 Power factor correction component

The power factor (PF) is a measure of efficiency for electricity use. At the same time, the power factor has an important influence on the performance of electric motors found in production machines used in a factory in the Industry 4.0 ecosystem. Improving the power factor through correction methods reduces the load on transformers and power conductors, leading to a reduction in power supply losses and increased sustainability.

For a power factor compensation circuit, I used a capacitor bank in five steps, the first two using 3 single-phase capacitors and the next 3 using three-phase capacitors, as follows:

- Step I: 3x 9.6μF, 0.83kvar, 1.6A, 525V;
- Step II: 3x11.6μF, 0.83kvar, 1.73A, 480V;
- Step III: 6.6μF, 1kvar, 1.4A, 400V;
- Step IV: 6.6μF, 1kvar, 1.4A, 400V;
- Step V: 9.95μF, 1.5kvar, 2.2A, 400V.

I developed a hardware consisting of a Ducati Energia R5 485 device controlling the capacitor bank and a Raspberry Pi 3 IoT device with the corresponding software, several command and control possibilities and a high degree of automation, the schematic is shown in Figure 4.9.

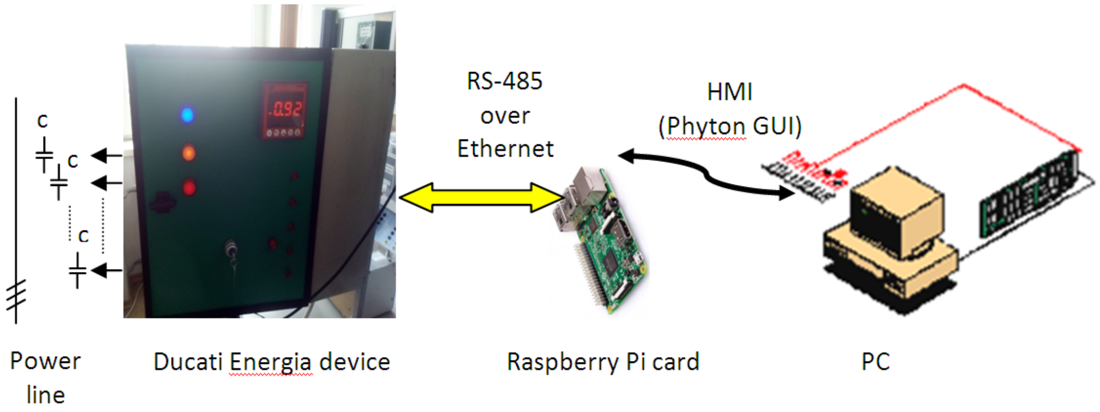

Fig. 4.9 Schematic representation of the proposed power factor correction assembly [6].

The application was developed in Phyton and the user interface is in the form of an HTML page for maximum application compatibility. The routes accessible to the application have been divided into two categories: public and private. Public routes are index and login, which are accessible to anyone, while private routes require username and password authentication and include read, admin and logout.

4.4 Conclusions of chapter 4

The personal and original contributions consist in the realization of a system for acquiring and monitoring the electricity parameters provided by smart meters to ensure power interruption in critical conditions, increasing safety in an Industry 4.0 factory. I have analysed ways of communicating between industrial equipment and have developed a different system for secure data transmission to cloud servers. I implemented cross-validation services, such as working time and machine uptime. I improved power grid parameters by adding a power factor correction component and made a novel connection between the capacitor bank controller and the overall Industry 4.0 system.

The research results presented in this chapter have been disseminated in other articles in the literature. The paper entitled *Electric grid monitoring and control architecture for industry 4.0 systems* was published in *2018 International Symposium on Fundamentals of Electrical Engineering (ISFEE)* [4]. The paper *Improving the Efficiency and Sustainability of Power Systems Using Distributed Power Factor Correction Methods* was published in the journal *Sustainability* [6].

Chapter 5

Quality assurance in composite manufacturing

Composite materials are fundamental to today's industrial environment, offering special characteristics that cannot be achieved using raw natural materials.

5.1 Composite production machinery

There are several techniques for manufacturing composites, including: hand lay-up, vacuum assisted lay-up, resin infusion, spraying, resin transfer moulding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM). Hand lay-up is a simple but efficient method that requires low capital investment to produce composite materials. Resin injection moulding methods lead to the highest quality products and the VARTM process, shown in Figure reffig:vartm, ensures that potentially harmful substances used are contained in the vacuum bag.

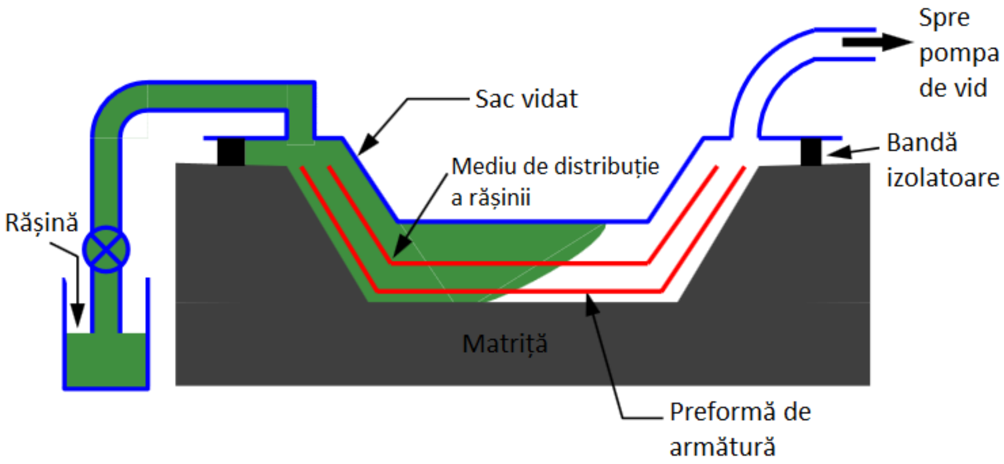

Fig. 5.2 VARTM process diagram [22].

This approach is being tested in the manufacture of multi-functional sandwich panels made from fibre-reinforced composite materials as building materials for construction applications. These panels can be used as partition wall elements, providing acceptable or even improved levels of sound and thermal insulation compared to conventional wall elements, as well as additional functions such as energy storage capabilities.

To achieve the required level of control, I propose a system based on distributed sensors that communicate with a central hub responsible for data aggregation, data interpretation and data-driven decision-making.

5.2 Sensors for production monitoring

The concept chosen for monitoring the production of composite materials is feasible. However, implementations require specific technological solutions, tailor-made for each occasion and independent of each other. To overcome these limitations, I have created a system that is modular, scalable and easy to interface with third-party Industry 4.0 systems, while also being easy to manage by users and operators who are not necessarily equipped with specific technological expertise.

To detect the presence or proximity of an object I used the infrared proximity sensor. Detection of ambient temperature, barometric pressure and humidity is performed by a separate and independent unit connected to the same common bus of the whole system. The final mechanical properties of composite materials depend to a large extent on the rheological events occurring during the polymerisation cycle. In particular, full-field measurement of temperature during the polymerisation phase of composite panels can provide important information about their mechanical behaviour [11].

5.3 Sensor network

In order to interconnect all the component modules with each other, I chose a bidirectional communication bus capable of supporting a dynamic number of components, without distinguishing between their role as master or slave. The MODBUS protocol defines the format and mode of communication between a “master” that manages the system and one or more “slaves” that respond to queries from the master. The protocol defines how the master and slaves establish and interrupt communication, how the sender and receiver are to be identified, how messages are to be exchanged and errors detected.

5.4 Case study on monitoring the manufacturing process of composite materials

A test facility architecture was designed and developed, taking into account the notes made in the previous sections and the targeted test scenario for the manufacturing of composite panels. The setup is built around a single Raspberry Pi board computer with integrated flash memory.

In the particular case of composite materials manufacturing, the sensors used in the array are: ambient temperature, ambient pressure, ambient humidity, ambient particle density for multiple particle types, and temperature array for monitoring each composite panel as it is produced.

To take advantage of the information provided by the distributed sensor network, the Raspberry single board computer was connected to an Industry 4.0 enabler hub using the specially developed API for this function.

In order to authenticate the single-board computers connecting to the main hub, each of them has a unique token generated by the system. Each API access point expects a JSON Web Token (JWT) provided in the jwt property of the request body.

The physical-cybernetic system described in this chapter represents a framework that can be adapted to create a scalable monitoring matrix for various sensors as needed.

5.5 Conclusions of chapter 5

Personal contributions consist of the architecture of the distributed production monitoring system, evaluation of viable sensors, implementation of data acquisition nodes, data transfer to the cloud using modern JSON-based technologies. By integrating a sensor array with an Industry 4.0 hub, data was made available to operators in a familiar environment, facilitating data-driven decisions.

The research results presented in this chapter were disseminated in the paper entitled *Distributed Sensors Array for Composite Materials Manufacturing Quality Assurance* which was published in *2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE)* [8].

Chapter 6

Just-in-time co-ordination in Industry 4.0 processes

The concept of Just in Time (JIT) is one of the most important concepts in technology developed by IT companies, which has come to be used in all fields. In an industrial context, JIT is a working methodology that helps increase competitiveness, mainly by reducing inventory. JIT is an active research theme in the field of Industry 4.0.

6.1 Planning process in JIT manufacturing

In the case of a custom furniture factory addressed in this paper, I customize and optimize the flow according to industry-specific attributes. Given that interior design projects with a degree of similarity are being worked on, frequently used raw materials are identified and a buffer stock is created within the factory. For occasionally used components, commercial relationships are sought with suppliers, including delivery times and price lists. In addition, contracts are made with several suppliers who can supply similar, substitutable products.

6.2 JIT Delivery

JIT delivery in a cyber-physical system is designed to support a JIT material flow process. The system balances material inventory based on real-time data and Industry 4.0 technologies. The concept of JIT was first defined in 1982 as “the action of having the right parts at the right time in the right quantity” [16]. This definition illustrates the concept very well in terms of raw material and finished product delivery, but it has been enriched with new concepts related to Industry 4.0 to be applicable in a modern factory with options to customize the finished product according to customer requirements.

The goal of the developed cyber-physical application was to replace the Kanban card theory with a digital, vertically integrated solution for machine-to-machine (M2M) communication. The concept presented in Figure 6.3 was to create a seamless flow of information between manufacturing order, material delivery, material stock and material consumption, as well as an automatic purchase order to the supplier.

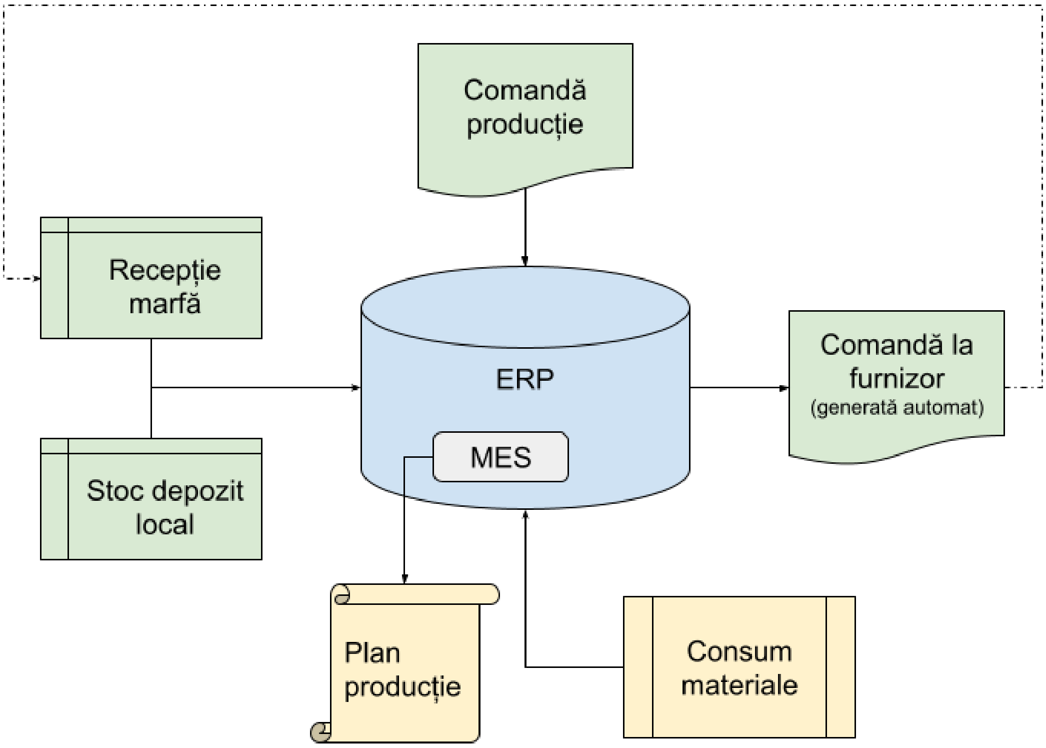

Fig. 6.3 JIT delivery for MES in Industry 4.0.

An additional benefit was the increased traceability and reliability of the process. The implemented JIT delivery enables the step-by-step elimination of stock in the factory warehouse and minimises the space required.

6.3 Conclusions of chapter 6

The original personal contributions consist of adapting JIT principles for sourcing and planning activities in the custom furniture production process. I have architected a dedicated IT system and implemented it as microservices within the overall Industry 4.0 system. In the user interface these are observed in the ERP component for resource management and in the MES component for production management.

Chapter 7

Systems Reliability in Industry 4.0

I had the opportunity to design and develop an Sensor-Cloud System(SCS) application to create a reference IoT architecture for smart products. Its goal is to transform information into knowledge throughout the product lifecycle, thus improving product and service quality, efficiency and sustainability.

7.1 Theoretical considerations on reliability in Industry 4.0

Data transmission plays a crucial role in any SCS application. The network is responsible for transferring data from sensors to the cloud, sending commands to decentralized sensor hubs and communicating decisions to actuators.

To define the average throughput, I use Claude Shannon's equation that defines the data transfer rate of a noisy channel, based on Nyquist's equation for noise-free channels, (7.1).

$$C = W \log_2 \left(1 + \frac{S}{N}\right) \tag{7.1}$$

The C capacity of a channel is the amount of information, in bits, that can be transmitted in one second over a channel having a W bandwidth and a S/N ratio of S signal to N noise.

7.2 Reliability calculation model

In order to measure and compare the reliability of SCS, an overall score is needed. I propose a formula based on the five main reliability domains discussed in the previous section, resulting in a sum of 5 factors R_x with their corresponding coefficients, K_x, according to the relation (7.3):

$$R = K_n R_n + K_r R_r + K_b R_b + K_t R_t + K_s R_s \tag{7.3}$$

Each of the reliability factors R_x is a percentage with a value between 0 and 1, while the coefficients K_x can be rearranged with the condition $K_x = 10$, resulting in a maximum reliability score $R = 10$.

Taking into account the impact that each of the five domains has on the SCS, I set the following coefficients:

- Network $K_n = 4$
- Recovery $K_r = 1$
- Backup $K_b = 1$
- Test $K_t = 2$
- Security $K_s = 2$

7.3 Experimental reliability testing and results

7.3.1 Network reliability

The reliability score was calculated for each scenario, taking into account an average bandwidth requirement of 20 Mbps. The results presented in Table 7.3 reveal a variation of 0.29 between the best and worst scenarios tested.

Tabel 7.3 Reliability of network communications [3].

Mod funcționare	**Latență**	**Rata retransmisie**	**Lățime de bandă**	R_n
Wireless Soft AP	0.247 s	13.78%	28 Mbps	0.643
Wireless Station	0.239 s	11.87%	35 Mbps	0.699
Cable	0.001 s	0.01%	100 Mbps	0.932

7.3.2 Testing the automatic recovery process

The test model was developed with automatic recovery for several components. The embedded device is set to resume operations after power outages, reboot itself when a sensor does not respond, and reboot, with optional firmware update, when requested by the cloud server. The test site experienced frequent short power outages. Recovery results were recorded as a comparison between a controller with automatic recovery enabled and one that required manual intervention.

7.3.3 Testing the local backup system

To test the local backup, a memory card rated at 8 GB capacity and UHS Class I was used. The controller was connected to 4 sensors, one being a Full HD camera recording an area with occasional motion. The internet connection to the cloud was broken to force local backup. Memory filled up to 90% in 3 hours and 46 minutes, resulting in an average bitrate of 4247 kbps.

7.3.4 Checking the automated software testing system

Average code coverage was 68%. The test reliability indicator, R_t, increased in this case from 0 to 0.68.

7.3.5 Security audit

To identify vulnerabilities to cyber attacks and to secure the system I used a set of predefined penetration tests [18]. A series of tests targeting the infrastructure and cloud web application were performed and a total of 2 high, 12 medium and 18 low security risks were identified. Using the reliability policy, vulnerabilities were identified and resolved. The Security Reliability Indicator improved from 0.238 to 0.833.

7.4 Conclusions of chapter 7

Five areas impacting system reliability were discussed and a new approach to improving IoT reliability was proposed, based on levels and oriented towards results. It is a new policy, proposed to ensure the reliability of an SCS by taking action in five main areas.

A new formula to measure and compare the reliability of complex SCS is presented. Reliability on a 10-point scale increased by more than 4.5 points for the system presented in this chapter, proving the effectiveness of the original reliability policy based on a multi-level approach.

In the article [3] in the list of original published papers, the method of assessing the reliability of the system is presented. It was disseminated under the title *Techniques to Improve Reliability in an IoT Architecture Framework for Intelligent Products* in the journal *IEEE Access*.

Chapter 8

Digital twin in Industry 4.0

The concept of Digital Twin (DT), refers to formal digital representations of a physical entity, process or system that capture the attributes and behaviours of that entity and are suitable for communication, storage, interpretation or processing in a particular context.

The digital brain is a concept that extends DT to cover the entire lifecycle of industrial products, thus transforming it into an intelligent entity with analytical and decision support capabilities. It facilitates the implementation of Manufacturing as a Service (MaaS).

8.1 Theoretical considerations on digital twin

The topic covered in this paper involves the creation of a complex IT system that serves the interests of many departments within an enterprise. In practice, IT solutions already exist for certain business needs, some of which have already been implemented in the company.

Microservices, or microservices-based system architecture, is an architectural style that structures an application as a collection of services that are easy to maintain and test individually, interconnected in a flexible way, and that can be deployed independently.

8.1.1 Cloud integrator system

The role of the cloud integrator system is to ensure communication between multiple services and expose a single interface to the user. Over time, several architecture templates for components within an IT system have emerged. At the server software infrastructure level, there are elements of microservice orchestration that are designed to bring all the components together into an integrated and unified information system.

8.1.2 Subsystem design

Using the AutoCad API system, dedicated applications were developed for parametric furniture design. The imos software is one such solution that uses parametric design as an algorithmically centred method. All furniture objects have attached metadata in the relational database. This data is used to generate bills of materials, cost estimates and quotations for the customer, lists of slabs with dimensions for cutting, labels for traceability of items in the factory, exploded drawings for assembly action, etc. Furthermore, this data is needed to realize the CAM function, the use of software and computer-controlled machinery to automate a manufacturing process. CAD information is used to generate toolpaths, actions such as cutting, drilling or milling, that machines perform to make a part. Post-processing converts the toolpaths into a language that CNC machines can understand.

8.1.3 Virtual presentation subsystem

Virtual reality can be an important tool for business development, bringing projects to life. Adoption of VR equipment is still low due to prohibitive costs. Therefore, a significant intermediate step can be to use existing technologies to present 3D models directly in the browser, offering the possibility of free exploration of space at scale like in a computer game.

8.1.4 Source code management

Continuous Integration (CI) is a practice that developers use to detect, locate and correct errors by frequently integrating code and running automated tests. Continuous Delivery (CD) ensures that CI-checked software is always in a ready-to-deploy state, reducing deployment time and creating a fast and efficient feedback loop between developers and users.

8.2 Experimental model of an IT system dedicated to a custom-made furniture company

Based on the theoretical concepts presented in the previous section, I have designed and implemented an IT system dedicated to a custom-made furniture company. Iwerp, short for Intelligent Wood Enterprise Resource Planning.

The main modules of Iwerp are shown in Figure 8.8. On the blue background are shown the modules essential for tracking projects, sales activity, supplier relationships and company resources. The yellow background shows the warehouse and production modules that ensure the organisation and operation of the custom furniture production plant. In addition, the staff module is used to record timekeeping, allocate work to projects and generate productivity reports per employee. The fleet module is dedicated to fleet and travel management. On the bottom line of the figure are represented the server modules that help the user interface with functions such as import and export of data, storage of files and relational data, API for connecting with other systems, processing of information for generating reports, etc.

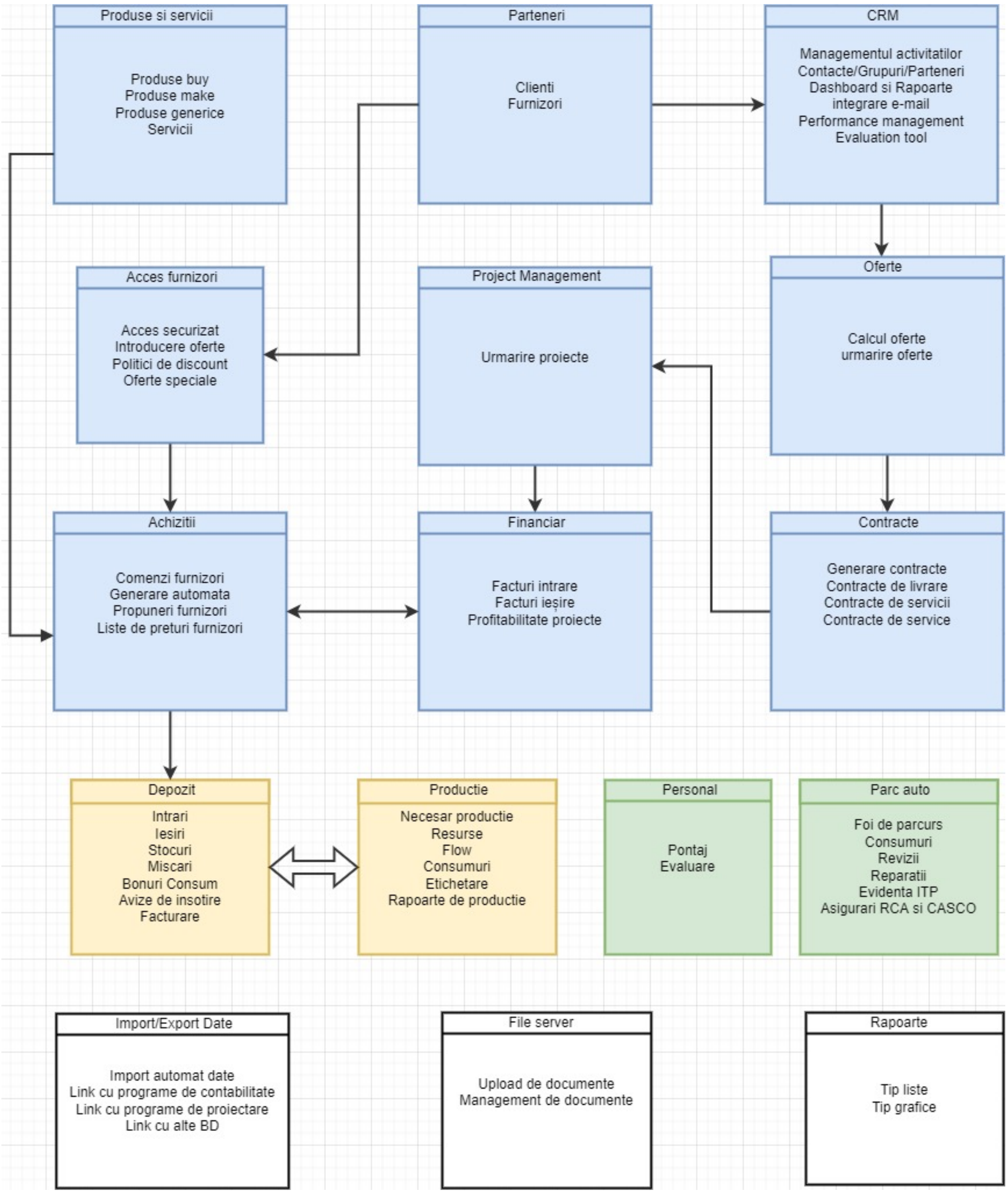

Fig. 8.8 Module diagram of the DT iwerp IT system.

8.2.1 Customer relationship management system

The DT system aims to create a flexible manufacturing system, a production method designed to easily adapt to changes in the type and quantity of the manufactured product. Machines and computerised systems can be configured to manufacture a variety of parts and to cope with changes. The first step in the business process is the relationship with customers, an activity tracked in DT through the Customer Relationship Management (CRM) microservice.

8.2.2 Microservices for project management

Opportunities automatically become projects when a bid proposed by the supplier is accepted by the client. The project microservice receives a range of information about the customer and their requirements from the CRM microservice. Once opportunities become projects, a main page is displayed in the menu that includes project details, status, progress and any comments. Actions for updating the project in the DT system are also available on this page as the implementation progresses in reality.

8.2.3 Microservices for raw material management

The Warehouse Microservice is responsible for the digital record keeping of all objects, goods and raw materials on the factory floor. Several warehouses can be defined with different locations and contact persons, and within each warehouse there can be several management. Quantitative stock is recorded by the warehouse managers and the financial value is linked to the invoices by linking them to the warehouse receipt/issue notes.

8.2.4 Microservices for production management

Production activities in the factory are digitally represented in the DT IT system. In chronological order of process flow, it starts with the display of the tender and contract estimates together with sketches and other files from the site. In the next step raw material lists are generated and saved in an internal order. For a quick import, I made a connection of the microservice with the MSSQL database of the imos CAD design system.

8.2.5 Catalogue of configurable fixtures

Using the tools provided by imos, I have created a catalogue of fixtures and fittings that cover most of the needs for furnishing a residential space. These fixtures were then parameterized to allow quick configuration of dimensions and other attributes such as: material decoration for the carcass and doors, number of poles, number of drawers, drawer mechanisms, hinges, lift systems, etc. The user interface is a form with various configuration options for each fixture type. The form is available as a window within the AutoCAD design program with the imos extension, but also in web format for the furniture manufacturer's online shop on demand.

The catalogue of configurable fixtures integrated in the DT system plays a very important role in quickly transforming the customer's requirements into technical drawings and execution details that are used for accurate cost estimation and project quotation, as well as for launching the production order to the factory.

8.3 Experimental testing in custom furniture manufacturing and results

The modular structure of the IT system made it possible to implement it in stages. To begin with, I have built the basic structure of the system and provided users with the module for organising information by project. Next, I implemented the microservices for stock records. Raw material requirements are automatically taken from the design, quantities available in the warehouses are updated in real time. Using these reliable information flows, together with the minimum/maximum stock rules and purchase orders being delivered, the DT system automatically generates purchase orders for the required quantities.

Input data from the design and warehouse microservices provides clarity to the factory manager who is in charge of planning the daily activity using the MES functions in the implemented DT IT system. The digital transfer of information between modules has led to the elimination of errors that occurred when manually copying data.

8.4 Conclusions of chapter 8

The personal and original contributions consist in the realization of the DT integrated IT system architecture, the design and implementation of working procedures for code management, the implementation of the furniture configuration system linked to CAD drawings with execution details, the realization of the interactive virtual presentation component in web format, the concept of interconnecting all systems in a standardized interface for employees, the implementation of links between data generated by components and the obtaining of high level information useful in business processes.

Chapter 9

Conclusions

The first three industrial revolutions led to standardised products. The steam engine, the mass production line and automation with robots all pursued the same goal, optimising product volume by optimising the production processes using standardisation and technological evolution. Henry Ford said "you can have the Model T in any color as long as it's black". The fourth industrial revolution is taking place right now, aimed at providing customised products using CPS.

Although the notion of Industry 4.0 has been intensively researched and tested over the last 10 years, there is still no consensus on a clear and specific definition. It is clear that all these efforts have had a positive impact on the industrial environment in general and there is still a huge potential in this area. Recognizing this potential, in my PhD thesis I focused on analyzing and synthesizing existing approaches and technologies, with the aim of realizing a tailored solution for the custom furniture manufacturing process, while retaining the possibility of horizontally expanding the applicability of the solution.

The aim of the system described in this paper is to achieve a high level of adaptability, predictability, reliability of the whole industrial and business process. This goal has been achieved by using a combination of the Internet of Things, cloud systems, system interconnection and advanced data analytics, among others. This new vision defines the Industry 4.0 ecosystem as a connected, yet decentralized set of service providers and service consumers within the factory, vertically and horizontally integrated to align with business, manufacturing and entire supply chain processes.

9.1 Obtained results

The IT system developed provides connectivity for decentralised systems to create an intelligent production environment capable of communicating and making optimal decisions. Key elements of the Industry 4.0 ecosystem specific to the furniture industry have been developed, while interconnecting and supporting technologies and products from any manufacturer. The technologies behind the solution are cloud-supported interconnectivity with a distributed architecture, secure communication protocols and procedural standards that are part of the modern manufacturing process.

9.2 Original contributions

Original contributions that I have published:

1. study on the influence of water-resistant box color on sensors inside [25];
2. power grid monitoring and control system for industry 4.0 systems [4, 5];
3. agricultural crop telemetry monitoring system [26];
4. distributed sensor system for quality assurance in composite manufacturing [8];
5. distributed power factor correction methods to improve efficiency and sustainability of power systems [6];
6. signal source location method for a sensor array [15];
7. reliability improvement techniques in an IOT architecture for smart products [3];
8. technology based on IoT, cloud and artificial intelligence for energy consumption assessment [7];
9. assessing the use of LIDAR systems in environmental protection [14].

Original contributions presented for the first time in this PhD thesis:

1. I have designed a strategy to apply JIT concepts in Industry 4.0;
2. I created a cloud-based microservices architecture for the furniture manufacturing industry;
3. I created a system for configuring furniture fixtures with direct link to CAD model;
4. I implemented a method to present VR and 3D interior design concepts in the browser;
5. I have used several programming systems to realize these computer systems. The metrics for the source code are as follows:
    - PHP: over 43,000 lines of code;
    - JavaScript: over 6,000 lines of code;
    - CSS: over 1,300 lines of code;
    - shell scripts: over 400 lines of code;
    - XML: over 230,000 lines of code;
    - SQL: over 130 tables.

9.3 List of original publications

Papers published in journals

- [26] Adrian ZARNESCU, Razvan UNGURELU, Mihai SECERE, **Ciprian Mihai COMAN**, Gaudentiu VARZARU, "*Putting Internet-of-Things at the service of* *sustainable agriculture. Case study: Sysagria*", Universitatea de științe agricole și medicină veterinară "Ion Ionescu de la Brad" din Iași, Facultatea de agricultură, **revista Lucrări Ştiinţifice (BDI)** publicata in EDITURA "ION IONESCU DE LA BRAD" IAŞI (tip B+, cod CNCSIS 477 pe site-ul revistei si 196 pe site-ul CNCSIS 2011-2012 de mai jos), vol. 62(1)/**2019**, seria Agronomie, pg. 9-14, Editura ISBN (print) 1454-7414, ISSN (electronic) 2069-6727, ISSN (CD-ROM) 2285-8148.

- [6] **Coman Ciprian Mihai**; Florescu Adriana; Oancea Constantin Daniel, "*Improving the Efficiency and Sustainability of Power Systems Using Distributed Power Factor Correction Methods*", **SUSTAINABILITY** Volume: 12 Issue: 8, Article Number: 3134 Published: **APR 2020**, Publisher MDPI, ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND, eISSN: 2071-1050; Web of Science Categories: Green & Sustainable Science & Technology (Q2/2019) Environmental Sciences (Q2); Environmental Studies (Q2); WOS:000535598700067; DOI: 10.3390/su12083134.
- [3] **Coman, Ciprian Mihai**, D'amico Giuseppe, Coman Adrian Viorel, Florescu Adriana, "*Techniques to Improve Reliability in an IoT Architecture Framework for Intelligent Products*", **IEEE ACCESS**, Volume 9, Page 56940-56954, DOI 10.1109/ACCESS.2021.3072168, **Published 2021**, ISSN2169-3536, Publisher IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC445 HOES LANE, PISCATAWAY, NJ 08855-4141; Web of Science Categories: Computer Science, Information Systems (Q2), Engineering, Electrical & Electronic (Q2), Telecommunications (Q2); WOS:000475904500025; DOI: 10.1109/ACCESS.2021.3072168.
- [7] **Coman Ciprian Mihai**; Florescu Adriana; Oancea Constantin Daniel, "*Assessment of Energy Use Based on an Implementation of IoT, Cloud Systems, and Artificial Intelligence*", **ENERGIES** Volume 14, Issue 11, Article Number 3202, Published: **JUN 2021**, Publisher MDPI, ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND, eISSN1996-1073; Web of Science Categories: Energy&Fuels (Q3); WOS: 000659844800001; DOI: 10.3390/en14113202.
- [9] **Coman, Ciprian Mihai**, Bogdan Corneliu Toma, Mihai-Alexandru Constantin, Adriana Florescu, "*Ground level LIDAR as a contributing indicator in an environmental protection application*", **Expert Systems with Applications** - ***în curs de recenzie din 28 martie 2022***.

Papers published at conferences

- [25] Zarnescu, Adrian; Ungurelu, Razvan; Macovei, Marius, **Coman Ciprian Mihai**, Varzaru Gaudentiu, "*Study of the Waterproof Shelter Colour Influence on the Atmospheric Temperature and Humidity Measurements for an Internet of Things Application*", Conference: 24th IEEE International Symposium on Design and Technology in Electronic Packaging (**SIITME 2018**) Location: Iasi, ROMANIA Date: **OCT 25-28, 2018**, Sponsor(s): IEEE; APTE; Univ Tehnica Gheorghe Asachi; IEEE Elect Packaging Soc; Politehnica Univ Bucharest, ISBN:978-1-5386-5577-1, ISSN: 2641-287X; Web of Science Categories:Engineering, Electrical & Electronic; WOS: 000466960400045; DOI: 10.1109/SIITME.2018.8599263.

- [4] **Coman, Ciprian Mihai**; Florescu, Adriana, "*Electric grid monitoring and control architecture for industry 4.0 systems*", Conference: International Symposium on Fundamentals of Electrical Engineering (**ISFEE 2018**) Location: Univ Politehnica Bucharest, Fac Elect Engn, Elect Engn Dept, Bucharest, ROMANIA Date: **NOV 01-03, 2018**, Sponsor(s): Assoc Romanian Elect Elect Engineers; IEEE Romania Sect CAS CS Chapter; IEEE, ISBN:978-1-5386-7212-9; Web of Science Categories: Engineering, Electrical & Electronic; WOS: 000480396400029; DOI: 10.1109/ISFEE.2018.87424
- [8] **Coman, Ciprian Mihai**; Florescu, Adriana; Stigliano, Giambattista, "*Distributed sensors array for composite materials manufacturing quality assurance*", Conference: 11th International Symposium on Advanced Topics in Electrical Engineering (**ATEE 2019**) Location: Bucharest, ROMANIA Date: **MAR 28-30, 2019**, ISBN:978-1-4799-7514-3, ISSN: 1843-8571; Web of Science Categories: Engineering, Electrical & Electronic; WOS: 000475904500025; DOI: 10.1109/ATEE.2019.8724867.
- [15] Constantin Daniel OANCEA, Dan OLARU, **Ciprian Mihai COMAN**; Adriana FLORESCU, "*Signal Source Location Problem in the Case of Sensor Network*", 12th International Symposium on Advanced Topics in Electrical Engineering (**ATEE 2021**) | 2021 12TH INTERNATIONAL SYMPOSIUM ON ADVANCED TOPICS IN ELECTRICAL ENGINEERING (ATEE), ISSN1843-8571; Web of Science CategoriesEngineering, Electrical & Electronic; WOS: 000676164800037; DOI: 10.1109/ATEE52255.2021.9425111.
- [14] Constantin Daniel Oancea, **Ciprian Mihai COMAN**, Bogdan Corneliu Toma, "*Evaluation of the Use of LIDAR Type Systems in Environmental Protection*", 2022 IEEE International Conference on Automation, Quality and Testing, Robotics **AQTR 2022**; DOI: 10.1109/AQTR55203.2022.9801922.

Papers presented at scientific symposia

- [5] **Coman, Ciprian Mihai**, and Florescu, Adriana, "*Electric grid monitoring and control architecture for industry 4.0 systems*", **SAD-ETTI 2019**;

Research reports

- Scientific report no. 1/2019, Report name: "*Electric grid monitoring and control architecture for industry 4.0 systems*".
- Scientific report no. 2/2019, Report name: "*Studiul impactului de culoare al adăpostului impermeabil asupra măsurătorilor de temperatură și umiditate atmosferică pentru o aplicatie IoT*".

- Scientific report no. 1/2020, Report name: "*Arhitectura de monitorizare si control al retelei electrice pentru sisteme din industria 4.0*".
- Scientific report no. 2/2020, Report name: "*Matrice distribuite de senzori pentru asigurarea calității producției de materiale compozite*".

Research contracts

- RECOMLABS. This work was supported in part by UEFISCDI (Executive Unit for Financing Higher Education, Research, Development and Innovation) under Grant ERANET-INCOMERA-RECOMLABS-3, through PNCDI III.
- POKET. This work was supported in part by UEFISCDI (Executive Unit for Financing Higher Education, Research, Development and Innovation) under Grant COFUND-ERANET MANUNET III-POKET, through PNCDI III.
- MEPHIFA - Monitoring environmental parameters and human influences in forest areas. This work was supported in part by Asociación de Empresas Tecnológicas Innovalia (INNOVALIA), under Grant DIH World OC1, through the Horizon 2020 research and innovation framework programme.

9.4 Perspectives for further developments

Given the rapid evolution of technology in general, and in the field of this paper in particular, the system and technologies presented in this paper cannot be considered complete. Prospects for continuous development are outlined to improve and optimise already implemented operational processes, but also to add new services taking advantage of the modular and scalable architecture of the system.

The MES component can be accompanied by a neural network for the simulation and prediction function. Thus, after proper training of the network, better production planning options could be generated and failure probabilities could be predicted more accurately based on the wealth of information gathered by sensors and human operators.

By implementing the system in other industries as well, novel situations and requirements will arise that will open up new research directions related to the main topic of this paper.

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