

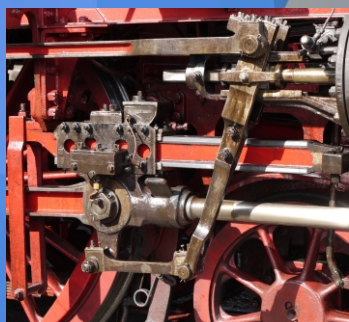
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Location estimation using wi-fi media access control address and device miniaturization

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Abstract: When location was estimated using Sigfox's Atlas Wi-Fi, the estimation error is several hundred meters. Meanwhile, when location was estimated using the Wi-Fi media access control (MAC) address and HERE's API, the estimation error was ~10 m. In an Internet of Things device that obtains the Wi-Fi MAC address, the combination of exp32 and 100a was ~1/5th of the combination of Arduino R4 and Sigfox Shield.

KEYWORDS: SIGFOX, WI-FI, MEDIA ACCESS CONTROL (MAC) ADDRESS, LOCATION

1. Introduction

Knowledge and information have not yet been exchanged in the information society (Society 4.0), which has resulted in problems stemming from a lack of interdisciplinary cooperation. Society 5.0 is expected to connect all people and things through the Internet of Things (IoT), which would enable the sharing of various types of knowledge and information.

From the perspective of using the Sigfox network and the Internet, we have developed an IoT device equipped with sensors for temperature, humidity, barometric pressure, and other signals to measure different physical data [1–5].

In the current study, we attempt to control Sigfox communication signals using AT commands with the Arduino UNOR4 Sigfox module. In addition, we attempt a social implementation using the proposed system.

In this study, we miniaturized a previously developed device that localizes using Wi-Fi media access control (MAC) addresses. We constructed a system that could display the information directly on smartphones, iPads, etc., and we studied the relationship between the size reduction rate and the location accuracy.

2. Experimental

2.1 What is Atlas? [6]

Launched in January 2017, Atlas Native is the first Sigfox location service that is based solely on the Sigfox network location. The Atlas Native service is available for every device equipped with even a simple Sigfox module, and even those without GPS or any other additional hardware/software component.

Following the launch of this service, Sigfox began working on the development of the Atlas Suite to enable all types of use cases that involved asset location by choosing appropriate technology(ies) for the right balance between cost, energy, and accuracy. The two live Atlas services include:

- Atlas Native, which provides Sigfox network-based location only
- Atlas Wi-Fi, which provides Wi-Fi positioning and Sigfox network location (fallback)

2.2 Atlas Native [6]

Atlas Native is based solely on the Sigfox network location service, aiming to provide the geographic coordinates (latitude/longitude) and an estimated radius of a device message delivered through a callback or a standard Sigfox API.

Table 1 Outline of Atlas Native, Atlas Wi-Fi, and Atlas Bubble

GEOLOCATION TECHNOLOGIES	CRITERIA				GEOLOCATION OFFERS		
	Accuracy	TCO	Battery consumption	Outdoor/ Indoor	atlas Native	atlas WiFi	atlas Bubble
sigfox	⬢	\$	🔋	++++	✓	✓	✓
wi-fi	⬢	\$	🔋	+++		✓	
Bubble by sigfox	⬢	\$	🔋	++			✓
GPS	⬢	\$	🔋	++			
					Location information X, Y, radius		

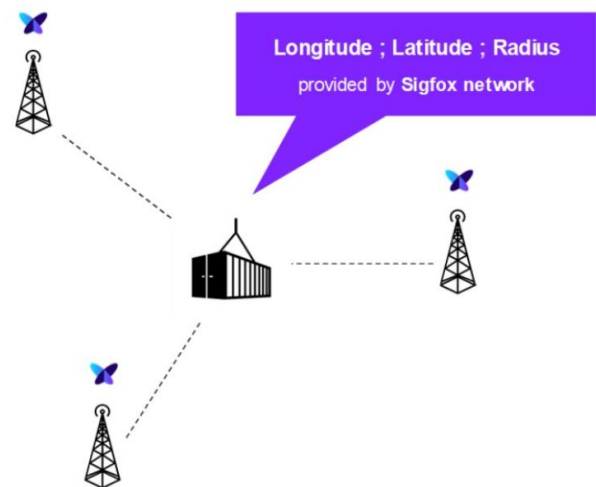


Fig. 1 Schematic diagram of Atlas Native

2.3 Atlas Wi-Fi [6]

Atlas Wi-Fi is a combination of two location technologies—Sigfox network and Wi-Fi positioning—into a single location service.

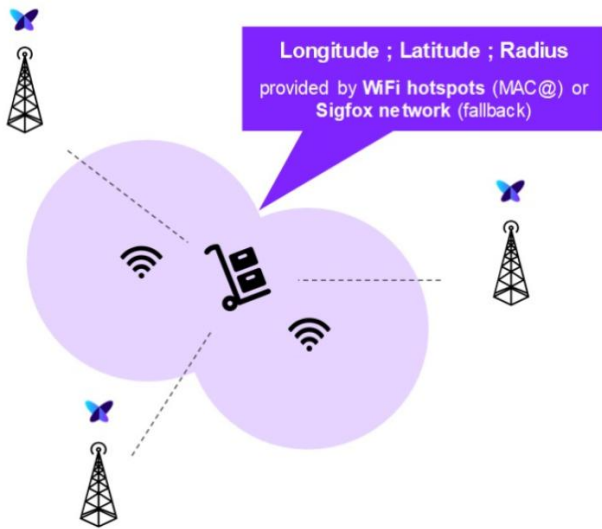


Fig. 2 Schematic diagram of Atlas Wi-Fi

Similar to Atlas Native, the service provides the geographic coordinates (longitude, latitude, and radius) and the estimated radius of a device message delivered through a callback or a standard Sigfox API.

By default, the coordinates are provided by the Wi-Fi location service, and the network location is used as a fallback solution (due to its low accuracy) and as a means to check the relevance of the Wi-Fi location—what we call a “consistency check” (due to possible Wi-Fi infrastructure updates).

2.4 Wi-Fi positioning

Google and HERE Technologies have large databases with several billions of Wi-Fi access points that are recorded and frequently updated worldwide. In March 2018, Sigfox chose HERE as its main provider for the Wi-Fi location service.

Since November 2018, HERE has been providing a Wi-Fi location with only 1 MAC@ sent by the device, whereas most Wi-Fi providers (including Google) attempt to collect and send to their platform at least 2 MAC@ for data privacy purposes. However, this regulation requires HERE to lower the level of accuracy of the Wi-Fi location when only 1 MAC@ has been sent by a device (+500 meters radius value).

2.5 Sigfox module

A Sigfox breakout board (SBB) was used as the Sigfox module (Fig. 3).



Fig. 3 SBB [BRKLSM100A] [7]

Key features: Compact module $14 \times 15 \times 2.8$ mm. (Typ.) LoRa™ modulation technology. Sigfox modulation technology. Sensitivity down to -136 dBm@LoRa (BW = 125 KHz, SF = 12) -124 dBm@Sigfox (0.6 Kbps). UART interface. Low-power long-range transceiver operating in the sub-1 GHz ISM band. Supply voltage range from 1.8 to 3.6 V. RF interface optimized to 50Ω . Output power level up to $+15$ dBm. STM32WLE5CC.

A program must be written to run the Sigfox module (Fig. 1) on a microcontroller, which generally requires a library. To reduce the program’s dependence on the microcontroller, we created the program using AT commands. In the future, we hope to create a microcontroller and dedicated CPU that can run AT commands.

2.6 Arduino UNO R4 Wi-Fi

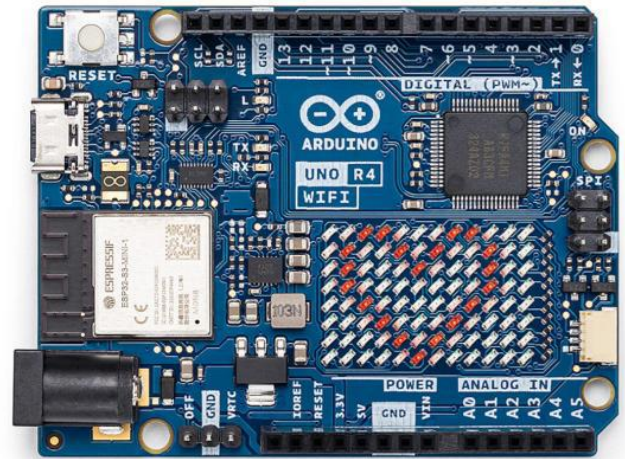


Fig. 4 Arduino UNO R4 Wi-Fi device [8]

The Arduino® UNO R4 Wi-Fi is the first UNO board to feature a 32-bit microcontroller and an ESP32-S3 Wi-Fi® module (ESP32-S3-MINI-1-N8). It features an RA4M1 series microcontroller from Renesas (R7FA4M1AB3CFM#AA0), based on a 48 MHz Arm® Cortex®-M4 microprocessor. The UNO R4 Wi-Fi memory is larger than its predecessors, with 256 kB flash memory, 32 kB SRAM, and 8 kB EEPROM. The RA4M1 operating voltage is fixed at 5 V, whereas the ESP32-S3 module uses a voltage of 3.3 V. Communication between these two MCUs is performed via a logic-level translator (TXB0108DQSR).

2.7 Assembling the Sigfox module and Arduino

The SBB was placed on a custom-manufactured printed circuit board (PCB). Figure 5 shows an IoT device that is configured by connecting a PCB to an Arduino UNO R4 Wi-Fi device.



Fig. 5 IoT device using Arduino with the Sigfox module

We have reported that it is possible to obtain the MAC addresses of nearby Wi-Fi antennas using an IoT device (see Fig. 5) [9]. To improve the portability of IoT devices, consideration should be given to creating containers and PCBs using 3D printers, miniaturizing antennas and integrated circuits, and reducing power consumption.

As part of a research project commissioned by the Chudenko Corporation, we have been using a 3D printer to create cases for small devices; one example is shown in Fig. 6.

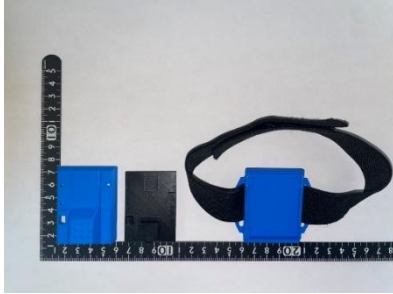


Fig. 6 Parts created with a 3D printer (from the left: the bottom of the case, a model of the part to be inserted, and the top of the case)

2.8 Improving the portability of IoT devices

To increase the portability of IoT devices,

1. Place the IoT device in a 3D case.
2. Select a small integrated circuit.
3. Select a small antenna.
4. Create a PCB.
5. Reduce the power consumption (energy saving).

First, we created a 3D case for the IoT device.

We used SOLIDWORKS® 3D CAD to design a 3D case for the IoT. SOLIDWORKS® 3D CAD is the recommended solution for professionals around the world who need to design innovatively, produce products faster, and achieve a high level of efficiency in their daily product development work. With decades of user-request-based enhancements and thorough research and development focused on the user experience, it is powerful and easy to learn and use [10].



Fig. 7 3D printer (Bambu Lab X1-Carbon Combo) [11]

The modeled data were created using SOLIDWORKS® 3D CAD and output using the Bambu Lab X1-Carbon Combo (see Fig. 7).

An IoT device built on Arduino with a Sigfox module (see Fig. 5) was inserted into the 3D case we fabricated to create an IoT device (see Fig. 8).



Fig. 8 IoT device built on Arduino with a Sigfox module in a 3D printed case (width 95 x height 65 x depth 40 = volume 247,000 mm³)

Next, the integrated circuit was selected.

The Arduino® UNO R4 Wi-Fi is the first UNO board to feature a 32-bit microcontroller and an ESP32-S3 Wi-Fi® module (ESP32-S3-MINI-1-N8). The Arduino® UNO R4 Wi-Fi comes with a 32-bit microcontroller and ESP32-S3 Wi-Fi® module (ESP32-S3-MINI-1-N8), but to miniaturize it further, we used the ESP32-S3 board with 16 MB of flash memory and no pin headers, ESP32-S3-DEV-KIT-N16R8 (see Fig. 9).



Fig. 9 ESP32-S3 Wi-Fi module (ESP32-S3-MINI-1-N8) [12]

Next, the small antenna was selected.

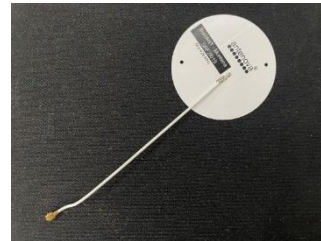


Fig. 10 Selector flat antenna [13]

A thin, flat antenna was used (see Fig. 10) rather than a rod-shaped antenna (see Fig. 3).

Next, a PCB was created.

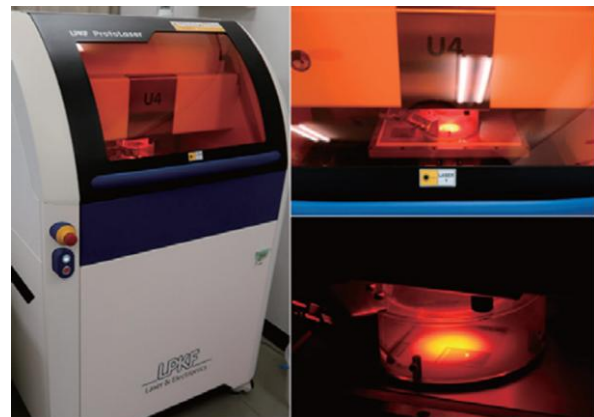


Fig. 11 Laser processing equipment for PCBs (The LPKF ProtoLaser U4 main body (left), with laser processing in progress (top right) and enlarged image of the processed area (bottom right) [14])

Using a laser PCB processing device (see Figure 10), we created a special PCB for miniaturization. The resulting board is shown in Fig. 12.



Fig. 12 Processed PCB

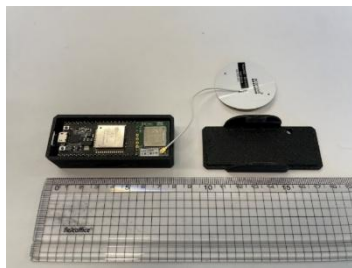


Fig. 13 IoT device created (width 90 x height 35 x depth 12 mm = volume 37,800 mm³)

A photo of the IoT device we created is shown in Fig. 13. After we attempted to miniaturize this IoT device, its volume was reduced to approximately one-sixth the volume that of the previous device (see Fig. 8).

3. Results and Discussion

Using the IoT device we created, we collected the MAC address information for the surrounding Wi-Fi antenna devices, and we obtained their locations (see Fig. 14).

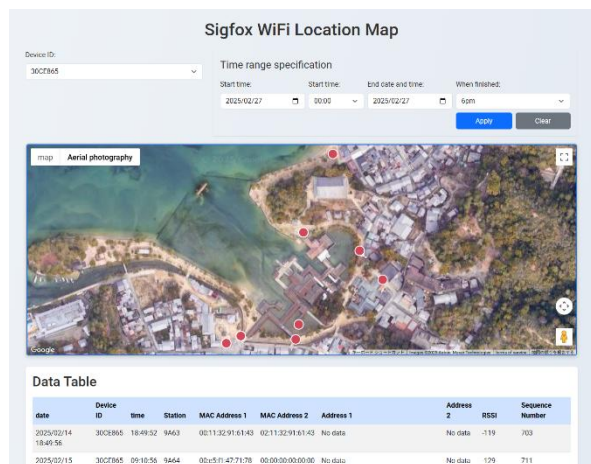


Fig. 14 Locations (Filled Red Circle) of the IoT devices obtained using the MAC addresses of nearby Wi-Fi antennas (World Heritage Itsukushima Shrine area)

When location was estimated using Sigfox's Atlas Wi-Fi, the estimation error was several hundred meters. Meanwhile, when location as estimated using the Wi-Fi media access control (MAC) address and HERE's API, the estimation error was ~10 m.

4. Conclusion

When estimating the location using Sigfox's Atlas Wi-Fi, the estimation error was several hundred meters. Meanwhile, when location was estimated using the Wi-Fi MAC address and HERE's API, the estimation error was ~10 m. In an IoT device that can obtain a Wi-Fi MAC address, the combination of esp32 and 100a was ~1/6 of the combination of Arduino R4 and Sigfox Shield.

We are currently building devices by combining electronic components. In the future, we would like to make IoT devices even more compact by surface mounting their components and using integrated circuits created by ASIC. Next, we would like to expand the range of social applications for this device by reducing its power consumption.

Acknowledgments

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MESWARM: A Modular and AI-Driven Manufacturing Execution System for Industry 4.0

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Abstract: The rapid advancement of Industry 4.0 technologies has significantly transformed manufacturing environments, necessitating the adoption of intelligent and scalable solutions. MESWARM is a modern platform designed to digitize and optimize manufacturing processes, offering industrial enterprises a means to enhance efficiency, reliability, and sustainability. By integrating traditional Manufacturing Execution System functionalities with cutting-edge technologies such as Artificial Intelligence and the Internet of Things, MESWARM provides a flexible, modular system tailored to specific production needs. Its architecture and key functionalities are outlined, highlighting its core modules such as Configuration, Production Management, and IoT. The potential of future modules, including Service Management, Adaptive Logic, Energy Management, Document Management, and AI-driven analytics, is also explored. By leveraging real-time data collection and analysis through MQTT-based communication, MESWARM facilitates precise production monitoring and predictive maintenance, minimizing downtime and enhancing operational decision-making. Real-world implementations are examined, showcasing its impact on production efficiency and system scalability.

Keywords: MANUFACTURING EXECUTION SYSTEM, INDUSTRY 4.0, INTERNET OF THINGS, ARTIFICIAL INTELLIGENCE, SMART MANUFACTURING

1. Introduction

In today's highly competitive industrial landscape, manufacturing enterprises face increasing pressure to optimize production processes while maintaining high quality and reducing operational costs [1]. Traditional Manufacturing Execution System (MES) solutions, while effective, often lack the flexibility and scalability required to integrate emerging technologies and evolving production demands [2]. The shift towards Industry 4.0 necessitates the development of more adaptive and intelligent systems that seamlessly connect various production components, providing real-time insights and enhanced control over manufacturing operations [3].

MESWARM is designed to address these challenges by merging conventional MES capabilities with modern digital innovations [4]. The platform introduces a modular approach, allowing businesses to configure and expand functionalities based on specific requirements [5]. By incorporating Artificial Intelligence (AI), Internet of Things (IoT), and advanced data analytics, MESWARM ensures efficient resource utilization, predictive maintenance, and improved Overall Equipment Effectiveness (OEE) [6].

The system is structured around several key modules that facilitate comprehensive production monitoring and control. The foundational Configuration module ensures seamless integration with different manufacturing setups, while the Production Management and IoT modules enable real-time tracking and data-driven decision-making [7]. Additionally, the planned implementation of AI-based analytics and energy management solutions further enhances MESWARM's potential to revolutionize industrial automation [8].

This article delves into the technical aspects of MESWARM, illustrating its architecture, core functionalities, and implementation strategies. By reviewing real-world applications, we showcase the system's impact on production efficiency, responsiveness, and versatility. Through this discussion, we demonstrate how MESWARM paves the way for a smarter, more connected, and future-ready manufacturing ecosystem.

2. MESWARM Active modules

MESWARM is a modern platform designed to digitize and optimize production processes, enabling industrial companies to improve the efficiency, reliability and sustainability of their lines. The system combines traditional MES functionalities with advanced technologies, such as artificial intelligence and IoT, providing flexible solutions adapted to the specific needs of users. The goal of MESWARM is the integration of key modules that enable comprehensive monitoring, control and analysis of all aspects of

production, from line configuration to predictive analytics. The system is scalable and open to adding new functionalities according to user needs, and each module is designed to facilitate the collection and processing of data directly from the line. Here are some active modules:

- **Configuration:** It allows simple setting and adjustment of production parameters according to the specific needs of the user. This module helps to set the basic rules and conditions of line operation. This is a common and mandatory module of any configuration.

- **Production Management (PM):** It provides a detailed overview of production flows, with the ability to monitor key parameters in real time. The focus is on achieving optimal efficiency and minimizing downtime.

- **Internet of Things:** This module connects equipment to a network of sensors, enabling real-time condition monitoring. IoT in the MESWARM system uses data from production lines for the possibility of short-term or long-term monitoring, optimization and predictive maintenance.

Other modules (under development or planned for implementation):

- **Service Management:** Monitors service and maintenance work, including all preventive and corrective activities.

- **Adaptive Logic:** Enables the adjustment of production rules depending on the real situation on the line.

- **Energy Management:** Monitors and optimizes energy consumption during production, enabling sustainability and efficiency.

- **Document Management:** Digital archive of technical documentation available in real time.

- **Artificial Intelligence:** Analyses line data to predict potential problems and provide recommendations.

- **New/customized modules:** The possibility of developing new functionalities according to the specific needs of users.

MESWARM provides a flexible data collection system, with a focus on key parameters such as: machine condition, energy consumption, temperature, load, duration of the production cycle, stoppages, work errors, etc. This data is used for advanced analytics that help make strategic decisions and optimize processes.

Simple and fast implementation: MESWARM is designed to be easily integrated into existing production systems without the need for significant downtime. The system can be implemented on

different types of lines and production processes with minimal adjustments, thus achieving rapid return value and adaptation.

Ease of use through the web application: the MESWARM web application provides an intuitive user experience through a customizable dashboard that the user can edit independently. Users have the ability to monitor only those parameters that are relevant to their roles – from line operators, to managers and maintenance teams. This enables personalized access to key information, increasing the efficiency and speed of decision-making.

2.1. Monitoring of key parameters from a real production line

Within MESWARM, the PM and IoT modules enable the collection and processing of key data from the production line, providing precise information necessary for analysis and optimization of production. This data collection principle is applicable to all system modules. The method of collecting data from the machines may vary depending on the state of production and technical conditions on the line. The most common approach involves using a Windows service, a small application installed on any computer within the company that is connected in a LAN to the PLC devices from which the data is collected.

In situations where this method is not possible, data collection can be realized by wire connection and sending it to a special PLC dedicated exclusively for that purpose. Regardless of the method chosen, the key goal is to process and send data via simple and clear MQTT messages. MQTT is a standard protocol for data transfer in IoT applications, which enables a high level of flexibility and reliability.

In the long term, this approach leaves users with the ability to independently generate and send standardized MQTT messages without the need for additional intervention from our team. In this way, the system remains scalable and allows for easy expansion or adaptation to specific user needs, thus reducing implementation and maintenance costs.

The defined JSON messages sent to the system via the MQTT protocol are designed to be clear, simple and flexible, enabling the collection of key information with a minimum number of mandatory data. The main advantage of this approach is that the system can function smoothly even when only the basic data set is sent, while all other information is optional and can be adapted to the specific needs of the user. The only mandatory parameter in the JSON message is the "R" status, while the other data is optional and allows additional information about the current state of the line, production and timestamps. An example of JSON messages for PM and IoT modules is given in Figure 1.

```

1 {
2   "S": {
3     {
4       "R": false,
5       "D": "Feeder motor error",
6       "T": 1615808155099
7     }
8   },
9   "PD": [
10    {
11      "N": "001",
12      "C": 10,
13      "Q": 100,
14      "T": 1615808095099
15    }
16  ]
17 }

```

```

1 {
2   "PM": {
3     {
4       "N": "x",
5       "V": "10"
6     },
7     {
8       "N": "y",
9       "V": "20"
10    },
11    {
12      "N": "z",
13      "V": "30"
14    }
15  ],
16  "T": 1615808155099
17 }

```

Fig. 1 Example messages for a) PM and b) IoT modules.

Explanation of key message elements - PM module:

- "S" (Status): List of objects containing:
 - "R" (Required): Mandatory parameter indicating the production status (e.g. whether production is in progress or stopped).

- "D" (Description): An optional parameter that provides a description of the current state (e.g. "No Material").

- "PD" (Production Data): List of objects with production data:

- "N" (Name): Name of the product (optional).
- "C" (Count): Number of units produced (optional).
- "Q" (Quantity): Quantity of material related to the current production cycle (optional).

- "T" (Timestamp): Timestamp of the message in milliseconds from the epoch (optional). IoT module:

- "PM" (Process Monitoring): A list of objects that records various process parameters from the production line. Each object contains the following fields:

- "N" (Name): Name of the monitored parameter. In this example, "x", "y" and "z" represent different parameters of the manufacturing process, such as temperature, belt speed or pressure.
- "V" (Value): Value of the measured parameter. For example, for "x" the value is 10, which may indicate a temperature of 10 °C, while the values for "y" and "z" may indicate other process quantities.

- "T" (Timestamp): A timestamp that records the moment when the data was collected. This allows accurate time synchronization of all parameters.

The flexibility of these formats allows users to send only the information that is available or necessary to them at a certain moment, and the system will automatically process the available data without compromising functionality. This approach simplifies the implementation of the system, enables easy integration with different types of equipment and provides the possibility of scalable expansion without the need for additional interventions. When data arrives at MESWARM cloud backend services, it is processed, stored in the most optimal form possible and delivered to clients via REST API so that all clients get a visual representation on their dashboards on the web application.

2.2. Parameters within the PM module on a specific production line

The PM module enables production status monitoring, downtime recording and product records, which is crucial for the calculation of OEE and related efficiency indicators. Key parameters include:

- *Production status.* Production status can be: "Production in progress" or "Production stopped". Also, the status can be "Unknown" in case the line does not send data (due to system shutdown or internet connection interruption). This situation is marked as "Out of Service", and data from this period is not included in the analysis of most Key Performance Indicators (KPIs).

- *Number of manufactured products.* Continuous monitoring of the number of valid and/or invalid products produced on the line (with the possibility of defining the percentage of validity that enables automatic monitoring of products from several quality classes). This information is crucial for analysing performance and overall efficiency.

- *Product names.* Records of different types of products that are produced on a specific line.

- *Downtime.* Automatically detected or manually entered outages are classified and used for availability analysis within the OEE calculation. Downtimes are monitored in real time to quickly identify and eliminate the causes of reduced efficiency. They can also be planned and unplanned and accordingly affect the calculation of key production efficiency indicators differently.

This data (except production status) is automatically pulled from the production process when possible or manually updated via the user interface. The following images show different real widgets from the dashboard of the web application for the mentioned line, which are part of the PM module:

• **Widget: Workstation control panel.** This widget, shown in Figure 2, allows online monitoring of the production status, the number of valid and invalid products produced, the name of the product and the type of downtime. In addition to monitoring, depending on the assigned privileges, users can edit data up to a certain level in terms of changing the number of valid or invalid products, editing downtime, etc.

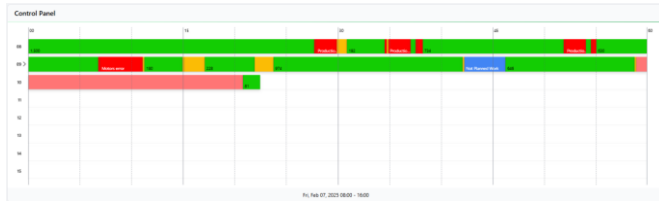


Fig. 2 Workstation control panel widget.

• **Widget: Downtime.** This widget, shown in Figure 3, allows online monitoring of the most common types of downtime in the desired time interval and over the desired part of production, which provides users with input information to react in order to reduce the time and frequency of downtime, which leads to an increase in production efficiency.

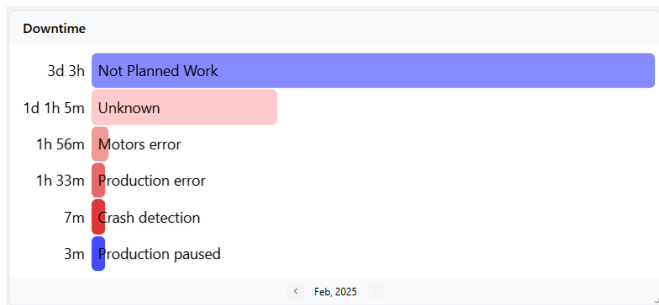


Fig. 3 Downtime widget.

• **Widget: Production.** This widget, shown in Figure 4, allows online monitoring of the number of different valid and invalid products produced in a desired time interval and over a desired part of production.

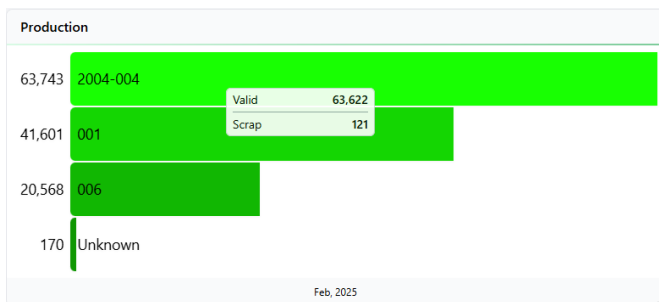


Fig. 4 Production widget.

2.3. Parameters within the Internet of Things (IoT) module on a specific line

In the IoT module, unlike the PM module, although we use a similar method of data collection via the MQTT protocol, sending data does not require prior configuration in terms of defining what data is sent and when. Data is automatically sent at predetermined time intervals, depending on the needs of the user and the specifics of the production process. Data sent at a certain time interval will be available for analysis and visible within the system only for the periods in which it was actively collected. This approach allows

users the flexibility to determine the frequency of data collection and their analysis according to their needs.

On a specific production line, we collect the following key parameters:

1. Safety indicators:

- *EStop1-Ok to EStop7-Ok*: Status of the emergency stop safety buttons (E-Stop) connected to different points of the line. These parameters detect possible errors and enable quick shutdown in case of danger.

2. System messages:

- *AutoStateErrorMessage*: Error messages in automatic mode.
- *ProductionStateErrorMessage*: Error messages that occur during the production process.

3. Tool strokes:

- *P1Strokes#, VBStrokes#, P2Strokes#, S1Strokes#, S2Strokes#*: The number of strokes performed by each key tool on the line. These parameters are used to monitor work intensity and plan maintenance. For example, different tools have a recommended maximum number of strokes before the tool blades need to be sharpened.

4. Layer and material parameters:

- *Layer.Name*: Name of the current layer in the process.
- *Layer.StepLaps[#]*: Number of step-laps in the current layer.
- *Layer.Same*: Number of identical layers in one process.
- *Coil.Width[mm]*: Width of the sheet metal currently in use.
- *Coil.Thickness[mm]*: Thickness of the sheet metal currently in use.

- *ShapesToDo[#]*: Number of shapes remaining to be processed.

- *ShapesPerProduct[#]*: Number of shapes per product.

5. Line and material speeds (Speed and feed rates):

- *PiecesPerMinute[PPM]*: Line speed in units of products per minute.

- *Material.Speed[mm/s]*: Speed of material movement through the line.

6. Material dimensions and positioning (Material dimensions and positioning):

- *Material.MinimumWidth [mm]* and *Material.MaximumWidth [mm]*: Minimum and maximum width of material supported.

- *Material.InLine*: Status of material on the line (whether it is present or not).

7. Hydraulics and control states (Hydraulics and control states):

- *HydraulicMotorTurnedOn*: Status of the hydraulic motor.
- *Stacker.InAuto*: Indication of whether the stacker is in automatic mode.

8. Drive parameters:

- *Drive.DCSupply.StatusWord*: Current status of the DC power word.

- *Drive.DCSupply.DCBus[V]*, *DCBus[A]*: DC bus voltages and currents.

- *Drive.DCSupply.Main[V]*: Main supply voltage.

- *Internal and External Brake Resistor Power/Peak Energy*: Monitoring the operation of the internal and external brake resistors.

9. Guidance and positioning parameters:

- *Guides.Position[mm]*: Position of the material guides.
 - *Feeder.Position[mm]*, *Velocity[mm/s]*, *Torque[%]*: Position, speed and torque of the feeder motor.
 - *Feeder.Error* and *Feeder.ErrorID*: Error indication and error code for the feeder motor.
10. Decoiler parameters:
- *Decoiler.Diameter[mm]*: Current diameter of the decoiler.
 - *Decoiler.Position[°]*, *Velocity[°/s]*, *Torque[%]*: Position, speed and torque of the decoiler motor.
 - *Decoiler.InAutoMode*: Indication of the decoiler automatic mode.
11. Axis parameters:
- *P1X*, *P1Z*, *P2X*, *P2Z*, *S1Z*, *S2Z*, *VBY*, *VBZ*: Positions, speeds, torques and status words for key axes on the line. These parameters allow precise tracking of the position and movement of each axis, which is crucial for the accuracy of the operation. Example of parameters monitored for the P1X axis. All of these parameters are monitored for each axis:
 - *P1X.AbsoluteCurrent[%]* – Absolute current on the P1X axis.
 - *P1X.AbsoluteVoltage[%]* – Absolute voltage on the P1X axis.
 - *P1X.ActivePower[%]* – Active power on the P1X axis.
 - *P1X.AmplifierOverloadUtilization[%]* – Amplifier utilization relative to maximum load.
 - *P1X.AplicationNominalUtilization[%]* – Nominal application utilization on the axis.

- *P1X.Busy* – Indication of axis busyness during task execution.
- *P1X.DCBus[A]* – Current on the DC bus.
- *P1X.DCBus[V]* – Voltage on the DC bus.
- *P1X.DigitalInputsState* – State of digital inputs on the axis, ie on the servo regulator (drive).
- *P1X.Enable* – Indication of whether the axis is enabled.
- *P1X.Error* – Axis error indication.
- *P1X.ErrorID* – Axis error code.
- *P1X.HeatSinkTemperature[°C]* – Drive heatsink temperature.
- *P1X.Main[V]* – Main drive voltage.
- *P1X.MotorPhaseU[%]*, *MotorPhaseV[%]*, *MotorPhaseW[%]* – Current in phases U, V and W.
- *P1X.MotorTemperature[°C]* – Motor temperature on axis P1X.
- *P1X.Position[mm]* – Axis position in millimetres.
- *P1X.StatusWord* – Current axis status (status word).
- *P1X.ThermalUtilization[°C]* – Thermal load of the motor.
- *P1X.Torque[%]* – Torque.
- *P1X.Velocity[mm/s]* – Axis movement speed in millimetres per second.

Figure 5 shows images of different IoT widgets with different parameters and time periods for production line.

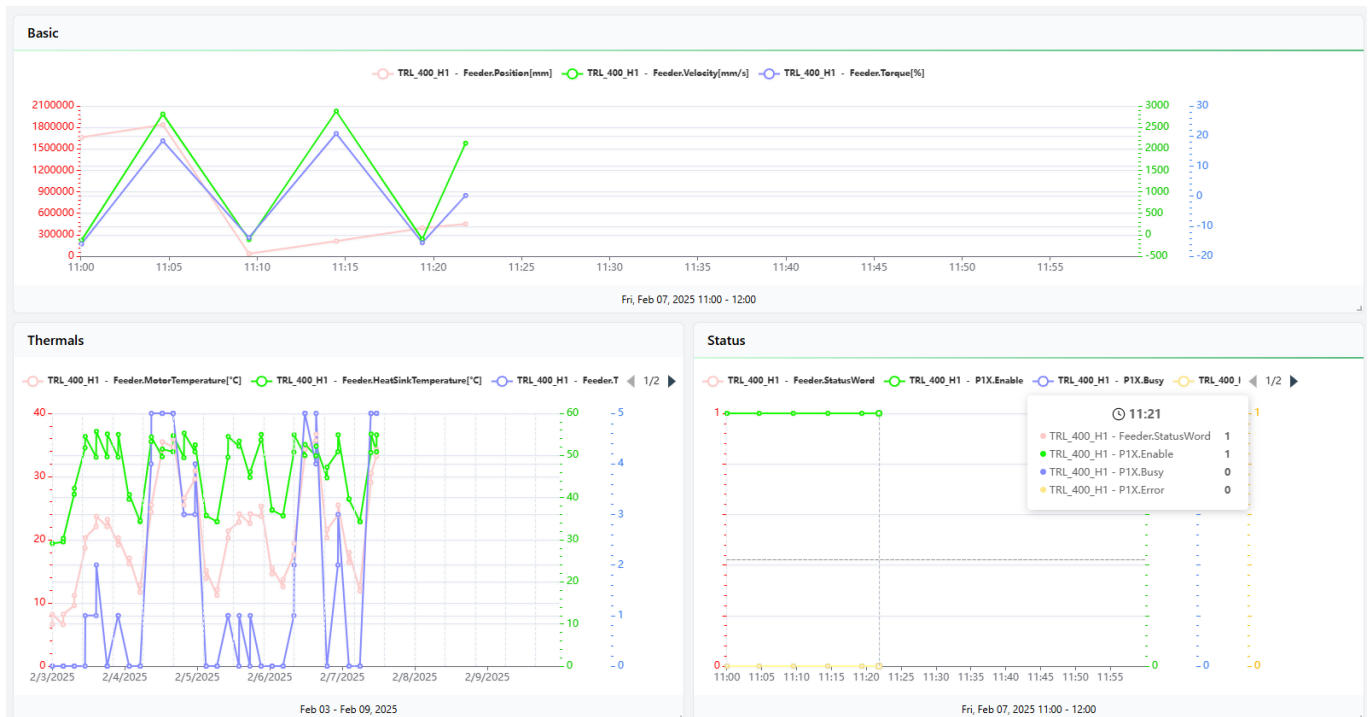


Fig. 5 Different IoT widgets with different parameters during first week of February 2025.

The changes to the parameters *Feeder.Position[mm]*, *Feeder.Velocity [mm/s]* and *Feeder.Torque[%]* in the upper Widget are shown, as well as *Feeder.MotorTemperature[°C]*, *Feeder.HeatSinkTemperature[°C]* in the Thermal Widget. The last window of the application called Status is a status Widget and current status values such as *Feeder.StatusWord*, *P1X.Enable*, *P1X.Busy* and *P1X.Error* are printed in it.

Figure 6 shows all temperatures for the entire month of January 2025, showing that the data started arriving on January 9th because the company was closed due to the holiday.

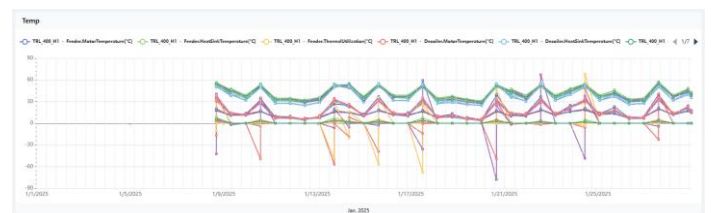


Fig. 6 Temperatures of different parts of the production line during the month of January.

In the front part of the diagram in Figure 6, the absence of parameters indicates that there was no production process during this period of the month.

3. Contribution of the MESWARM Solution to Increasing Industrial Production Efficiency

Figure 7 illustrates the status of the automated production line for the periods of August and September 2024. MESWARM was implemented on this line at the end of July 2024, and prior to that, there was no system for monitoring any production indicators. The figure uses green to indicate periods when the line was in automatic production mode, grey for when it was turned off and not transmitting data, red for unplanned downtimes, and blue for planned downtimes.

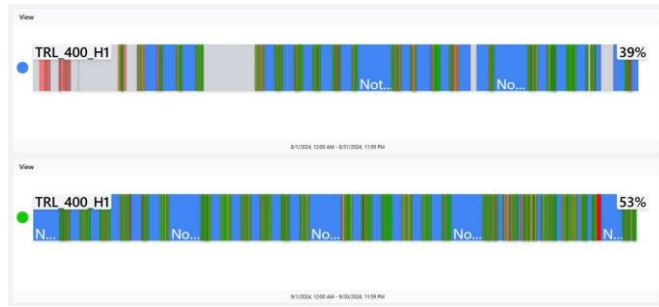


Fig. 7 Status of the same production line for August and September 2024.

A key advantage of MESWARM lies in its ability to enable real-time monitoring of all relevant production parameters. The PM module provides:

- Monitoring of production status, whether the line is active, in downtime, or in preparation;
- Recording and classification of downtimes - planned and unplanned stops, reasons for interruptions;
- Logging of valid and defective products, including product names if available.

This data enables a precise analysis of OEE parameters, including machine availability, performance, and production quality. By tracking downtime causes and bottlenecks in the production process, MESWARM supports decision-making aimed at reducing unplanned interruptions and improving equipment utilization.

Figure 8 presents a comparative analysis for the same period as in Figure 7, showing OEE and other key efficiency indicators. The figure displays all crucial indicators related to production efficiency. Notably, this production line does not have an automatic system for detecting defective products, meaning the quality metric is at 100%. In cases where such detection exists or when operators manually enter data retroactively, the quality metric may fall below 100%, affecting the overall OEE value.



Fig. 8 Comparative analysis and OEE widget display for August and September 2024.

Additional widgets allow tracking the number of valid and defective products produced within a selected period are also available. Users with the appropriate privileges can retroactively

modify certain data, such as unknown downtime reasons that could not be automatically detected, the number of valid and/or defective products, etc. (Fig. 9).

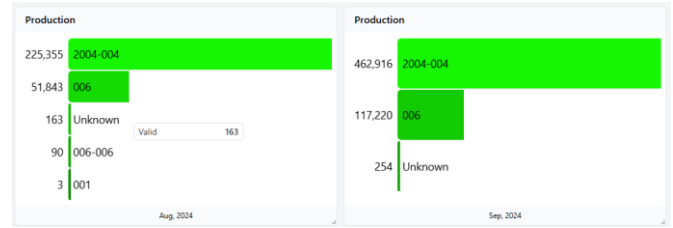


Fig. 9 Comparative analysis and display of the Production widget for August and September 2024.

3.1. Brief Explanation of OEE Calculation and Other Efficiency Indicators

OEE is a key metric for measuring production equipment efficiency and is calculated as the product of three main factors:

$$OEE = Availability \times Performance \times Quality \quad (1)$$

Where are:

• **Availability** – The ratio of effective machine operating time to planned production time, excluding unplanned downtime. It is calculated as:

$$Availability = \frac{Effective\ operating\ time}{Planned\ production\ time} \times 100\% \quad (2)$$

• **Performance** – The ratio of actual production speed to the theoretical maximum production speed:

$$Performance = \frac{Actual\ production\ speed}{Maximum\ production\ speed} \times 100\% \quad (3)$$

• **Quality** – The ratio of the number of valid products to the total number of produced units:

$$Quality = \frac{Number\ of\ valid\ products}{Total\ number\ of\ produced\ products} \times 100\% \quad (4)$$

Another efficiency indicator are Total Overall Equipment Effectiveness (TOEE) and Utilization. TOEE is an extended metric that includes both planned and unplanned downtimes in the Availability calculation. While standard OEE considers only unplanned downtimes, TOEE also accounts for planned stops, such as preventive maintenance, breaks, and equipment adjustments.

• **Utilization** indicates how much of the total available production time is effectively used. It is calculated as:

$$Utilization = \frac{Effective\ operating\ time}{Total\ calendar\ time} \times 100\% \quad (5)$$

3.2. Preventive Analysis of IoT Parameters and Issue Resolution Before Negative Impact

The IoT module in MESWARM enables real-time data collection from machines, sensors, and drive systems, providing valuable insights into equipment performance and operational status. The collected data includes:

- Safety system statuses (E-Stop sensors, operational errors);
- Tool cycle count and predicted maintenance intervals;
- Servo drive parameters (position, speed, torque, motor temperature);
- Voltage and current levels in bus systems, as well as braking resistor loads.

By continuously monitoring these parameters, MESWARM facilitates predictive maintenance, where the system can automatically detect potential failures before they occur. Early detection of anomalies allows operators to take preventive action, reducing unexpected downtime and avoiding costly breakdowns.

For example, if the temperature of a motor on a specific axis consistently increases over time, the system can trigger an early warning notification, prompting maintenance teams to investigate the issue. This pre-emptive intervention prevents overheating,

which could otherwise lead to excessive wear, reduced equipment lifespan, or complete failure.

Additionally, when a machine failure occurs, such as a motor error, MESWARM enables in-depth analysis by correlating multiple data sources. By examining multiple widgets covering the same time frame, operators can identify the root cause of the issue. Figure 10 illustrates a comparative display of two widgets, showing the precise moment when a "Motor Error" event occurred.

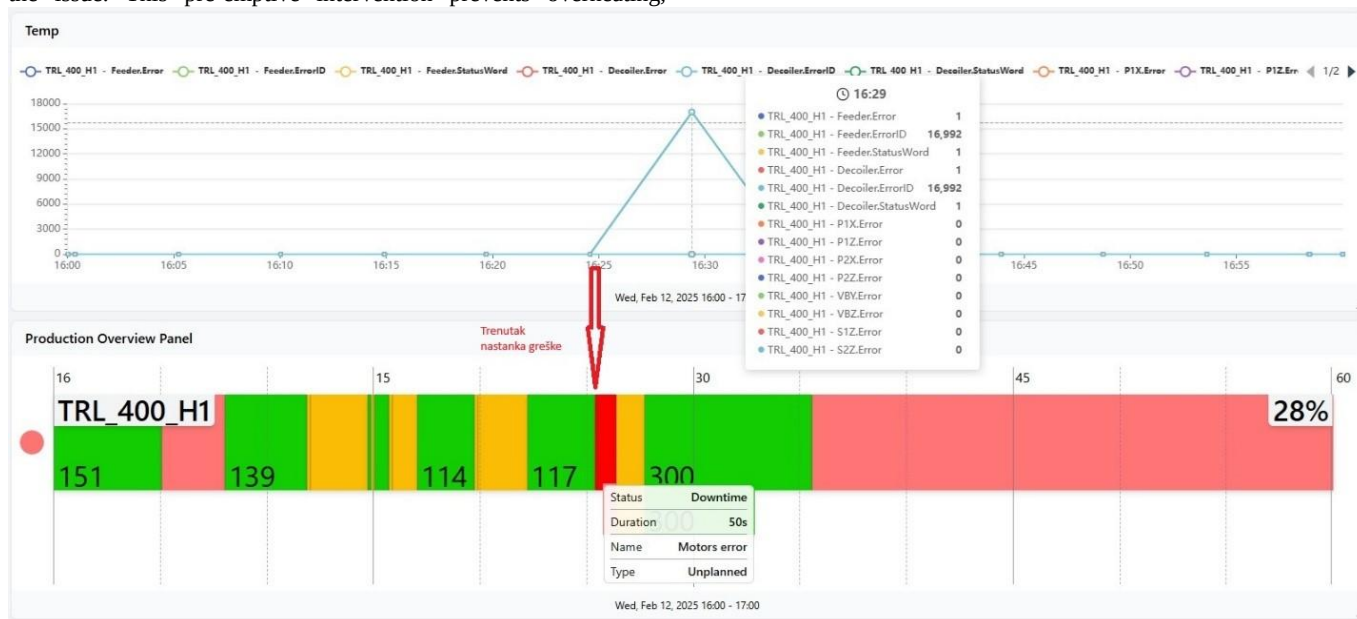


Fig. 10 Comparative analysis and display of the IoT and Production Overview widgets for the same period.

At the same time, the IoT graph reveals that the failure originated from issues in the feeder and unwinder axes, providing additional information such as the exact error ID from the control software. This data-driven approach allows maintenance teams to address failures more efficiently, reducing investigation time and improving overall system reliability.

By leveraging IoT analytics for real-time diagnostics and predictive insights, MESWARM helps manufacturers minimize unplanned downtime, extend equipment lifespan, and optimize production efficiency.

4. Conclusion

The digitalization of production processes is becoming a key factor in optimizing industrial plant operations. Modern solutions such as MES software allow manufacturing companies to monitor, analyse, and optimize their production workflows in real time.

This study examines the contribution of the MESWARM system to increasing efficiency, reducing downtime, minimizing material waste, and decreasing the number of defective products, as well as leveraging IoT analytics for predictive maintenance.

Implementing MESWARM in industrial production lines provides multiple benefits that significantly enhance efficiency and reduce production costs. By tracking key production parameters, optimizing material usage, and enabling predictive maintenance, MESWARM allows for: reduction of unplanned downtimes through timely diagnostics, minimization of waste and increase in valid product count through precise material tracking and optimal equipment performance maintenance while reducing failure risks. However, MESWARM alone does not bring improvements simply through implementation. It requires active engagement from users, who must act on the insights and reports generated by the system to achieve tangible benefits.

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2D graphene layers in chemiresistive sensors

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Abstract: In this paper, a two-dimensional (2D) material graphene with exceptional electronic and mechanical properties is discussed as a promising candidate for chemiresistive sensor applications. High surface area and superior charge carrier mobility of graphene enable rapid and sensitive detection of gaseous analytes, making it an attractive alternative to conventional metal oxide semiconductor (MOS) sensors. The review of recent advancements in graphene-based chemiresistive gas sensors is done, highlighting their operational principles, fabrication techniques, and performance enhancements through material modifications such as reduced graphene oxide (rGO). Additionally, we examine the application of graphene sensors in environmental monitoring, where their ability to detect pollutants like NO₂, NH₃, and CO₂ with high sensitivity and low power consumption provides a significant advantage over traditional sensing technologies. Despite these advancements, challenges such as selectivity, standardization, and sensor stability remain critical areas for future research.

Keywords: GRAPHENE, REDUCED GRAPHENE OXIDE, CHEMIREISTIVE SENSOR

1. Introduction

Graphene, a two-dimensional (2D) material composed of a hexagonal arrangement of carbon atoms, has garnered significant attention in various technological fields, particularly in sensor development, owing to its exceptional electronic and mechanical properties [1]. The escalating demand for real-time monitoring of hazardous gases and volatile organic compounds (VOCs) in diverse environments, ranging from industrial settings to domestic spaces, has spurred intensive research into flexible, cost-effective, and easily integrable sensor technologies.

Graphene, with its unique attributes, emerges as a promising candidate for chemiresistive gas sensors, offering a compelling alternative to traditional bulk materials [1], [2]. This review delves into the current research landscape of graphene-based sensors, encompassing chemiresistive gas sensors, environmental monitoring, and biological sensing.

We explore their operational principles, fabrication methodologies, performance characteristics, and prospective advantages over conventional sensing technologies, culminating in a cohesive overview of graphene's transformative potential in sensor applications.

2. Recent advances in graphene-based chemiresistive gas sensors

The intrinsic properties of 2D graphene layers are pivotal to their efficacy in chemiresistive gas sensors. Graphene's exceptionally high surface area, reaching up to 2630 m² g⁻¹, facilitates efficient adsorption of gas molecules, thereby enhancing sensitivity [1], [3]. Furthermore, its remarkable electron mobility enables rapid charge carrier transport, crucial for swift sensor response [1], [3]. Unlike conventional semiconductor metal oxide (MOS) gas sensors that often necessitate high operating temperatures, graphene-based sensors can operate at room temperature (RT), significantly reducing power consumption and mitigating safety hazards associated with flammable gases [1], [4]. MOS sensors, while widely utilized, suffer from drawbacks such as limited lifespan, poor selectivity, and high operating temperatures, rendering RT graphene sensors a more attractive option for many applications [1], [4]. The sensing mechanism of graphene chemiresistors is based on the modulation of graphene's electrical conductivity upon gas molecule adsorption [5]. This adsorption process, driven by weak van der Waals interactions, hydrogen bonding, or charge transfer, alters the charge carrier concentration in graphene [5]. Oxidizing gases, acting as electron acceptors, withdraw electrons from graphene, increasing hole concentration (for p-type graphene) and consequently decreasing resistance. Conversely, reducing gases, acting as electron donors, introduce

electrons, leading to increased electron-hole recombination and a rise in resistance [1], [5], [6]. This direct transduction of gas adsorption into a measurable electrical signal forms the basis of graphene's chemiresistive sensing capability [5].

While pristine graphene exhibits high sensitivity, its lack of active functional groups on the surface can limit chemisorption and result in slow recovery times and reduced selectivity [1], [7]. To overcome these limitations, researchers have explored various surface modification strategies. A cost-effective approach involves utilizing reduced graphene oxide (rGO), a derivative of graphene with adjustable optical and electrical properties, obtainable through economical synthesis processes [1]. rGO possesses oxygen-containing functional groups that can enhance gas molecule interaction. Further advancements involve hybridizing graphene or rGO with metal oxides, noble metal nanoparticles (NPs), and conducting polymers [1], [4], [8]. For instance, decorating graphene with gold (Au) NPs has been shown to enhance sensitivity and recovery in ammonia (NH₃) gas sensing [9]. Similarly, palladium (Pd)-functionalized multilayered graphene nanoribbon networks demonstrate exceptional sensitivity to hydrogen (H₂) at ppm levels with rapid response and recovery at room temperature [10]. Metal oxide/graphene hybrids, such as SnO₂/graphene, exhibit improved response to VOCs like benzene and ethanol compared to pure metal oxides [11], [12]. Chemical modification of graphene has also proven effective, with chemically modified graphene-based chemiresistors showing enhanced response, sensitivity, selectivity, and reversibility towards nitrogen dioxide (NO₂) detection compared to rGO [13]. Furthermore, graphene's cross-sensitivity to humidity can be mitigated, enabling selective detection of gases like carbon dioxide (CO₂) even in humid environments [14].

The fabrication of graphene-based chemiresistive sensors encompasses various methods. Chemical Vapor Deposition (CVD) is a widely used technique for producing high-quality graphene films [9]. However, for cost-effective large-scale production, rGO, synthesized through chemical reduction of graphene oxide, offers a viable alternative [1]. These graphene materials can be deposited onto substrates using techniques like drop-casting, spin-coating, or inkjet printing to create the sensing layer [15]. Interdigitated electrodes (IDEs) are commonly employed as contacts for chemiresistive sensors, facilitating efficient electrical signal transduction upon gas interaction with the graphene sensing layer [16]. Recent progress includes the development of compact sensor systems capable of monitoring hundreds of graphene sensors simultaneously, paving the way for sophisticated sensor arrays and electronic nose applications [17].

Table 1 summarizes various rGO/graphene-based chemiresistive gas sensors, showcasing the diversity of analytes detected and the performance metrics achieved [17].

Table 1. *rGO/Graphene-based Chemiresistive Gas Sensors*

No	Sensing Material	Analyte	Conc. (ppm)	Working Temp. (°C)	Response (%)	Ref.
1	Graphene	NH ₃	75	150	3.8	[4]
2	AgNPs/rGO	NO ₂	15	RT	40	[18]
3	Pd/Graphene	NH ₃	100	150	2.04	[19]
4	Al/Graphene	NO ₂	1.2	150	2.89	[19]
5	Ag/rGO	NH ₃	1	RT	6.52	[20]
6	SnO ₂ /rGO	NH ₃	50	RT	0.92	[21]
7	SnO ₂ NRs/rGO	NH ₃	200	RT	1.3	[22]
8	TiO ₂ /rGO	NH ₃	10	RT	0.62	[23]
9	TiO ₂ /rGO	CO	100	RT	1.12	[24]
10	NiO/rGO	CH ₄	1000	260	15.2	[25]
11	ZnO/rGO	CH ₄	1000	190	12.1	[26]
12	ZnO NWs/rGO	NO ₂	5	RT	3.5	[27]
13	ZnO/rGO	NO ₂	1.5	RT	1.1	[27]
14	ZnO/rGO	H ₂ S	8.1	RT	0.87	[27]
15	WO ₃ /rGO	NO ₂	0.5	RT	1.19	[28]
16	Cu ₂ O NRs/rGO	NH ₃	200	RT	2.04	[29]
17	CuO/rGO	NO ₂	1	RT	14	[30]
18	PTh/rGO	NO ₂	10	RT	26.36	[31]
19	P3HT/rGO	NH ₃	50	RT	12.63	[32]
20	PANI/rGO	NH ₃	100	RT	344.2	[12]

Despite the significant progress, challenges remain in realizing the full potential of graphene-based chemiresistive gas sensors. Selectivity remains a key concern due to graphene's inherent sensitivity to a wide range of gases. Functionalization and hybridization strategies are crucial to enhance selectivity towards specific target analytes [1]. Furthermore, standardization of graphene quality and production processes is essential for ensuring sensor reliability and reproducibility, as variations in graphene quality can significantly impact sensor performance [1], [33].

3. Graphene for environmental monitoring

The pervasive issue of environmental pollution necessitates the development of advanced sensor technologies for effective monitoring and mitigation strategies [1]. Traditional methods often suffer from limitations in sensitivity, selectivity, portability, and real-time detection capabilities [1], [2]. Graphene-based sensors offer a compelling solution to these challenges, leveraging their unique properties for enhanced environmental monitoring. As discussed in [1], graphene's high surface area and exceptional electron mobility are particularly advantageous for detecting trace amounts of gaseous pollutants and VOCs. Chemiresistive graphene sensors, operating at room temperature, present a low-power, cost-effective alternative to conventional high-temperature MOS sensors for monitoring air quality [1], [4].

Graphene and its derivatives, particularly rGO, have been extensively explored for detecting a wide range of environmentally relevant gases. Table 1, adapted from Sharma et al. [1], highlights the diverse applications of graphene-based chemiresistive sensors in environmental monitoring. For instance, sensors utilizing AgNPs/rGO composites exhibit a significant 40% response to 15 ppm of NO₂ at room temperature [18]. NO₂, a major air pollutant, can be effectively monitored using such graphene-based devices, offering improved sensitivity and lower detection limits compared

to traditional sensors [13]. Similarly, SnO₂/rGO hybrids demonstrate promising performance in NH₃ detection at room temperature [21], [22]. Ammonia, another critical environmental pollutant, can be detected with sensitivities ranging from 0.92% to 1.3% for 50-200 ppm concentrations using different SnO₂/rGO configurations [21], [22]. Furthermore, graphene's ability to detect CO₂ with negligible cross-sensitivity to humidity makes it suitable for reliable CO₂ monitoring in ambient air [14]. Smith et al. [6] demonstrated a graphene-based CO₂ sensor with stable response and rapid response time, highlighting its potential for real-world environmental monitoring applications.

The versatility of graphene allows for the detection of other environmentally significant gases such as methane (CH₄) and hydrogen sulfide (H₂S) using different graphene-based composites like NiO/rGO and ZnO/rGO [25], [27]. These examples underscore the broad applicability of graphene chemiresistive sensors in addressing diverse environmental monitoring needs, from industrial emissions to urban air quality assessment. The ongoing development of functionalized graphene and hybrid materials promises to further enhance the selectivity and sensitivity of these sensors, paving the way for more accurate and comprehensive environmental monitoring networks.

4. Conclusions

Graphene-based chemiresistive sensors have demonstrated significant potential in advancing sensing technology, including gas detection, environmental monitoring, and biological sensing. The exceptional electronic, mechanical, and structural properties of graphene, such as its high surface area, superior electron mobility, and room-temperature operation, make it an ideal candidate for next-generation sensors. Unlike traditional metal oxide semiconductor (MOS) sensors, graphene sensors offer lower power consumption, higher sensitivity, and faster response times, enhancing their practicality for real-world applications.

Modifications such as reduced graphene oxide (rGO) have significantly improved selectivity, response time, and stability. These advancements enable the detection of critical pollutants like NO₂, NH₃, and CO₂ with improved precision. Despite these advancements, further research and standardization of graphene synthesis and sensor fabrication techniques are crucial to ensure consistency and reproducibility in sensor performance.

5. Acknowledgments

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Ionospheric Radio Reflection Analysis System Solar Flare and Sunrise/Sunset Interference Detection

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Abstract: Traditionally, solar flare detection has been achieved through methods that rely on the presence of expensive satellites. We propose an alternative method that produces reliable detection of solar flares in a cheap and conveniently earth-based way. This paper discusses the design, practical implementation, demonstration of functionality and usefulness of a reception and monitoring system for VLF (Very Low Frequency, 3 kHz–30 kHz) radio signals, transmitted by stations located thousands of kilometers from the reception point, that can be used to accurately detect solar flares. We chose this frequency range because VLF radio waves are efficiently reflected by the lower layers of the ionosphere, and diurnal or sudden changes in these layers cause corresponding variations in the received signal level over long distances (over 1000 km).

KEYWORDS: IONOSPHERE, VLF RADIO WAVES, SKY/GROUND WAVE, SOLAR FLARES, GEOMAGNETIC STORM

1 Introduction

Intense solar flares are accompanied by strong X-ray emissions. The sudden increase in X-ray intensity can be detected by Earth's artificial satellites about 8 minutes after the flare begins. Intense solar flares cause a rapid increase in the intensity of the solar wind and the kinetic energy of the constituent particles. After a few dozen hours, when it reaches the proximity of the Earth's magnetic field and is largely composed of electrically charged particles, the solar wind interacts violently with the Earth's magnetic field, causing intense geomagnetic storms. These geomagnetic storms can result in significant damage or even destruction of telecommunications equipment and power distribution networks.

In this paper we explore a new way of measuring solar flares by using VLF (Very Low Frequency, 3 kHz–30 kHz) radio signals transmitted by stations located thousands of kilometers from the reception point. We chose this frequency range because VLF radio waves are reflected by the lower layers of the ionosphere, and diurnal or sudden changes in these layers cause corresponding variations in the received signal level, over long distances (over 1000 km).

ELF/VLF waves are scientifically valuable because they primarily reflect off the Earth's ionospheric D region (60–90 km altitude) (See Figure 1 for ionosphere layers) and propagate efficiently within the Earth-ionosphere waveguide over global distances. This reflectivity makes ELF/VLF waves a unique tool for remote sensing of the D region, which responds to various inputs such as solar activity, lightning energy, electron precipitation from the radiation belts, cosmic gamma rays, and earthquakes. [5] The ionization of neutral molecules and the recombination of free-charged particles constitute a dynamic process strongly influenced by solar radiation. As a result, the ionosphere's lower layers appear at altitudes of 60–70 km during daytime (D layer) and at 90–100 km at night (E layer). During the night, the absence of direct solar energy causes the D layer to disappear due to the recombination of free-charged particles in this atmospheric region.[3]

VLF radio waves received at a long distance from radio transmitters have two components: ground wave (travels along the earth's surface) and sky wave (reflected by ionosphere). [4] See Figure 2.

These two components can combine constructively or de-

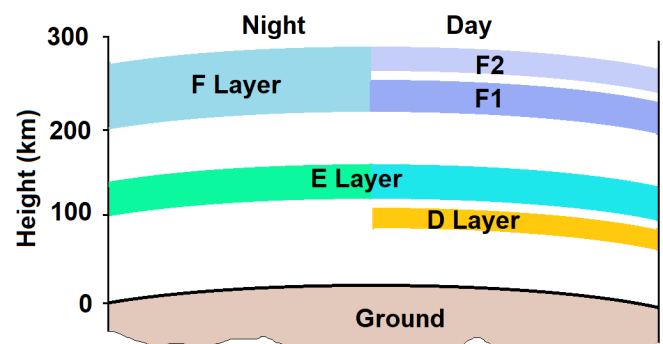


Figure 1: Diurnal Variation of Ionospheric Layers

structively at the reception point, depending on the path difference between the two propagation paths.

The main idea of this paper is the following: A solar flare will create a strong X-ray burst, which, once it reaches Earth, will influence the ionosphere's thickness, resulting in a shift between the stable ground wave and the sky wave. This shift can result in either constructive or destructive interference, depending on the shift distance and initial phase difference between the two waves. Some radio signals may experience a rise in amplitude while other may drop. This variation can be detected and compared with results from other stations or satellites.

2 Methods

2.1 Equipment

2.1.1 Receiving Loop Antenna

Antenna Housing. The antenna housing was constructed using a 35 mm diameter, 1 mm thick copper pipe, serving both as a structural support for the windings and as an electrostatic shield against noise from stray

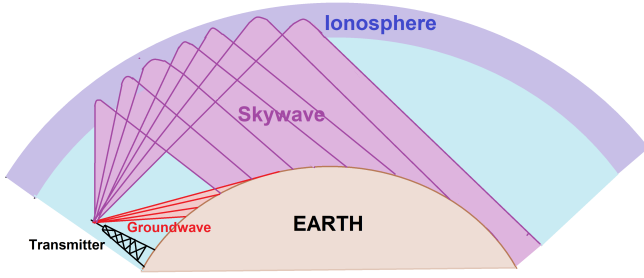


Figure 2: Ground Wave and Skywave Radio Paths

electric fields. The pipe was assembled into a square frame with an 850 mm side length, resulting in an approximate surface area of 0.72 m². See Figure 3 for magnetic loop antenna.

Coil Windings. A 30-turn coil was constructed within the housing, using 1.5 mm² solid-core copper wire (H07V-U). Thick insulation was selected to ensure more spacing between windings, decrease total capacitance and thus significantly raise the resonant frequency of the antenna.



Figure 3: Magnetic Loop Antenna

2.1.2 Signal Amplifier

High Sensitivity Low Noise Amplifier

The OPA134 operational amplifier [7] was selected for its ultra-low distortion (0.00008%), low noise (8 nV/ $\sqrt{\text{Hz}}$), and suitability for audio-frequency amplification. An OPA2134PA package was used, with the two internal amplifiers configured in parallel to reduce noise and improve the signal-to-noise ratio.

External Laptop Sound Card

An external Steinberg UR22C sound card was used to add a second amplifying stage, improve signal reception and work as a digital signal processor, also offering a wider reception band from 0-96kHz as it has a sampling rate of 192kHz.[6]

2.1.3 Digital Signal Analysis

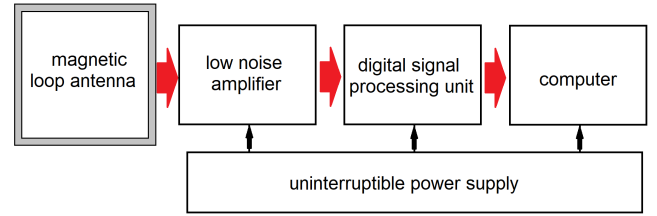


Figure 4: Bloc Diagram of Complete Assembly

To record and analyze the signal, Spectrum Lab [2] was employed in combination with Microsoft Excel on an HP Elite-book.

We chose to analyze radio transmitters based in Europe in order to avoid too many reflections off the ionosphere but also keep signal strength relatively high. We analyzed signals coming from DHO38 (Rhauderfeh, Germany), HWU (Rosnay, France), TBB (Didim, Turkey) and TFK (Grindavik, Iceland), but later abandoned TFK as the signal suffered too many reflections from the ionosphere resulting in poor quality.

2.2 Measurements

2.2.1 Solar Flare Measurement / Sunset-Sunrise Analysis

Solar flares happen over longer periods of time compared to lightning strikes, so the settings here aim for higher frequency resolution, less noise and higher amplitude measurement accuracy. We have increased the FFT setting to 1048576, and set smoothing to 6 with an averaging value of 64 seconds. We started measurements at roughly 5:20 UTC, before sunrise in Marisel, Romania, and ended at 16:20-16:30 UTC, after sunset. [8] The data for each day was periodically (every 20s) exported into a separate text file. The text file was later imported into Excel and the data was analyzed and plotted.

3 Experimental Results

3.1 Signal Reception

In Spectrum Lab, we observe multiple peaks along 19 kHz to 25 kHz. These peaks are from nearby VLF transmitters in Europe whose signals we can receive. The strongest signals are depicted in Fig 5. See Figure 6 for more information about depicted radio stations.

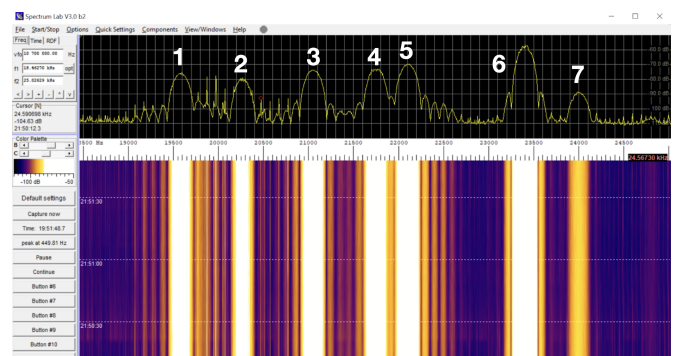


Figure 5: VLF Stations - Spectrogram Depiction

Nr.	Frequency (kHz)	Signal Strength (dB)	Call Sign	Location	Coordinates	Path Length (Km)
1.	19.58	-76	GQD	Anthorn (UK)	54.912833 N 3.254280 W	2053
2.	20.27	-80	ICV	Sardinia (Italy)	40.085899 N 8.979820 E	1352
3.	? 21.05	-74	?	?	?	
4.	21.75	-73	HWU	Rosnay (France)	46.700809 N 1.212702 E	1459
5.	22.1	-70	GVT	Skelton (UK)	54.001148 N 1.133000 W	2025
6.	23.40	-58	DHO38	Rhauderfehn (Germany)	53.133893 N 7.554132 E	1321
7.	24	-89	NAA	Cutler, Maine (USA)	44.657478 N 67.204132 W	6615

Figure 6: VLF Stations in Figure 5

3.2 Solar Activity & Sunrise/Sunset

The figure below represent the radio signal intensity versus time on 27.01.2025, received at Marisel, Romania (46.659458 N, 23.109890 E). See Sunrise/Sunset times for this location here : [8]

27.01.2025

We start measurements at 5:30 UTC and see a loss of signal from DHO38 between 7:00 UTC and 7:50 UTC. This corresponds to the transmitter being off presumably due to maintenance. At 8:00 UTC we can observe a sudden rise in signal strength both on TBB and DHO38 while on HWU the signal drops slightly. This perfectly aligns with measurement from the GOES satellite [1] (See Figures 7 and 8), which sends information about X-ray flux at geostationary orbit distance from Earth. The spike in our signal can be attributed to a class M2.6 solar flare.

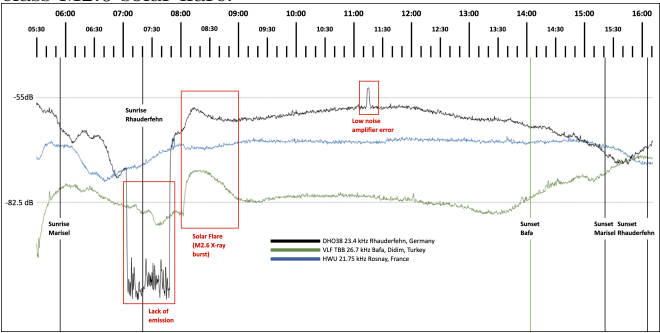


Figure 7: VLF Signal 27.01.2025

4 Discussion

Our results clearly show that our method is well suited for detecting solar flares and sunrise/sunset signal fluctuations. The shape of the detected solar flare also perfectly showcases the sudden ionization and gradual recombination of charged particles in the ionosphere. [3] Furthermore, as Bafa is most eastern, then Rhauderfehn and then Rosnay most western, in these early hours of the morning, the incidence angle between the suns rays and the radial direction of the Earth (at those points) decreases respectively. This means that more eastern locations suffer a greater flux variation (in the morning) during a solar flare (the X-ray flux is higher here, a direct result of the cosine of a smaller angle) as can be seen by comparing signal variations in all three locations. This

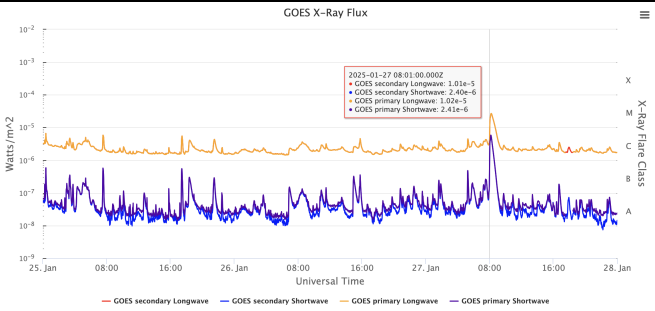


Figure 8: GOES X-ray Flux on 27.01.2025

system has proven to accurately relay information that can be used to detect an incoming solar geomagnetic storm dozens of hours before it hits, as well as detect lightning storms in the area. However, our method has a few limitations. First, it is directional (Flux is maximum through the antenna if it's aligned with the transmitting radio station), as it can only efficiently receive radio signals when it is oriented along the transmitters direction, and in an area with minimal radio noise. Second, our method only reliably works during daytime (Solar flares cannot be detected if the antenna is not on the side of the earth facing the Sun). Finally, it relies on artificially created radio signals. The last two limitations are characteristic of the system itself, but the first issue can be solved by having two antennas positioned at a 90 degree angle to each other, each receiving and analyzing signals. This configuration allows the system to not only measure signal intensity but also determine the direction which it is coming from. Future work will be needed to demonstrate this potentially improved set-up.

5 Conclusion

VLF radio signal monitoring is a reliable, cheaper and convenient Earth-based way of detecting solar flares, which could be useful to predict geomagnetic storms (created by strong solar flares) or to detect lightning activity in the range of a few thousand kilometers.

6 Acknowledgements

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Isentropic analysis of the complex three cylinder steam turbine from municipal solid waste power plant

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Abstract: In this paper are presented isentropic analysis results of a steam turbine and each of its cylinders which operate in Municipal Solid Waste (MSW) power plant. Low Pressure Cylinder (LPC) which produces the highest real mechanical power has the lowest isentropic loss of all cylinders equal to 4344.75 kW, while High Pressure Cylinder (HPC) which produces the lowest real mechanical power has the highest isentropic loss of all cylinders equal to 5204.54 kW. Isentropic losses and isentropic efficiencies are reverse proportional, because the cylinder with the lowest isentropic loss (LPC) has the highest isentropic efficiency equal to 88.92%, while the cylinder with the highest isentropic loss (HPC) has the lowest isentropic efficiency equal to 84.58%. Surprisingly, isentropic efficiency of the Intermediate Pressure Cylinder (IPC) is equal to 86.80% only, which is higher in comparison to HPC but notably lower than LPC. The observed turbine strongly differs from other comparable steam turbines from the literature where IPC has notably higher isentropic efficiencies than both HPC and LPC. Whole observed steam turbine produces real mechanical power equal to 97513 kW, while its isentropic efficiency is equal to 86.87%.

KEYWORDS: ISENTROPIC ANALYSIS, COMPLEX STEAM TURBINE, TURBINE CYLINDERS, MUNICIPAL SOLID WASTE (MSW)

1. Introduction

Steam turbines are nowadays the dominant mechanical power producers worldwide [1, 2]. Produced mechanical power by the steam turbines is dominantly used for the electrical generators drive and electricity production [3, 4]. However, steam turbines can also be used in various power plants as auxiliary turbines for the direct mechanical power consumer's drive [5, 6].

High power steam turbines are dominantly composed of several cylinders (usually three to five cylinders) mounted on the same shaft [7, 8]. Medium and low power steam turbines are usually composed of two, or only one cylinder [9, 10].

In complex steam turbines, each cylinder usually has several steam extractions [11, 12]. Each steam extraction delivers a certain amount of steam to the components of condensate/feedwater heating system which increases water temperature before its entrance to the steam generator and in that way reduces fuel consumption [13, 14].

In addition, complex steam turbines dominantly possess steam re-heater which additionally increases steam temperature after its expansion in the first cylinder [15, 16]. Steam re-heater can be mounted in the power plant independently of steam generator, but the most usual arrangement is that steam re-heater is mounted inside steam generator and uses the same fuel as other steam generator components [17].

This paper presents an isentropic analysis of a complex three cylinder steam turbine which operates in Municipal Solid Waste (MSW) power plant. Isentropic analysis is simultaneously performed for the whole observed steam turbine as well as for each of its cylinders. The obtained results are compared to the isentropic analysis results of various similar steam turbines. It is concluded that isentropic efficiencies of the analyzed steam turbine cylinders show some notable differences in comparison to similar turbines from other power plants.

2. Description and characteristics of the analyzed steam turbine

Analyzed steam turbine operates in a power plant which uses Municipal Solid Waste (MSW) as a fuel [18]. Steam turbine consists of three cylinders (High Pressure Cylinder – HPC, Intermediate Pressure Cylinder – IPC and Low Pressure Cylinder – LPC) connected to the same shaft which drives an electric generator, Fig. 1. As can be seen from Fig. 1, HPC has only one steam extraction (at the end of the cylinder), IPC has four steam extractions, while LPC has three steam extractions. HPC extraction and first two steam extractions of the IPC deliver a certain steam mass flow rate to high pressure feedwater heating system [19, 20], while third IPC extraction delivers steam to the deaerator. Last IPC extraction and all three LPC extractions deliver a certain steam mass flow rate to low pressure condensate heating system [21, 22]. After expansion in LPC, the remaining steam mass flow rate is

delivered to the main condenser. It should be highlighted that this power plant also possesses steam re-heater, traditionally mounted between HPC and IPC inside steam generator. Steam re-heater increases steam temperature and prepare it for the expansion in IPC and LPC. Steam re-heating process has many benefits not also in this, but also in many other steam power plants [23, 24].

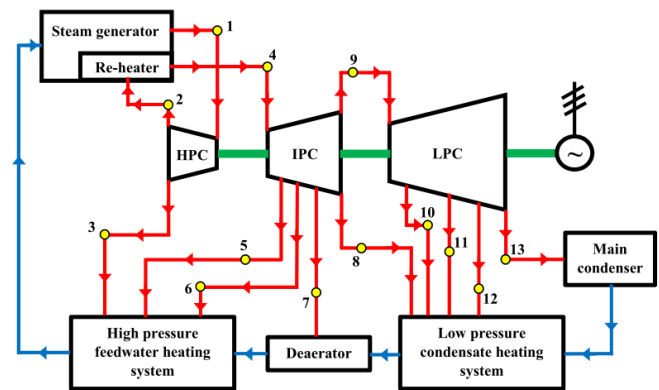


Fig. 1. General scheme of the analyzed steam turbine along with operating points required for the isentropic analysis

This paper presents the isentropic analysis results of the whole observed steam turbine and each of its three cylinders.

Isentropic analysis is based on a comparison of real (polytropic) and ideal (isentropic) steam expansion processes in each cylinder and whole turbine. Real (polytropic) steam expansion process is defined by operating points presented in Fig. 1 and Fig. 2 (points defined by numbers only) and its main characteristic is an increase in steam specific entropy during expansion. From Fig. 2 can be clearly seen that steam specific entropy increases from operating point 1 to 2 (HPC), from operating point 4 to 8 (IPC) and from operating point 9 to 13 (LPC). Increase in steam specific entropy during expansion is proportional to losses which occur in the turbine stages. Data in each operating point for real (polytropic) steam expansion process can be obtained only by the measurements during turbine exploitation.

Ideal (isentropic) steam expansion process is the process between the same pressures and it uses the same steam mass flow rates as real (polytropic) process, but in ideal process steam specific entropy remains constant during the expansion in each turbine cylinder. Ideal (isentropic) steam expansion process in each cylinder is defined using operating points with additional index – is, Fig. 2. Therefore, from Fig. 2 can be seen that steam specific entropy remains constant in the ideal expansion related to the HPC (operating points from 1 to 2is), IPC (operating points from 4 to 8is) and LPC (operating points from 9 to 13is). For each turbine cylinder, data related to the ideal (isentropic) steam expansion process are obtained mathematically, by knowing the steam

pressure in each operating point and by knowing steam specific entropy at the cylinder inlet. In comparison to real steam expansion process, ideal (isentropic) steam expansion process did not consider any losses which occur in turbine stages, what means that mechanical power developed in each turbine cylinder (as well as in the whole turbine) will always be higher in ideal than in real expansion process [25]. The ideal steam expansion actually represents maximal potential which can be used in any turbine cylinder and in the whole observed turbine.

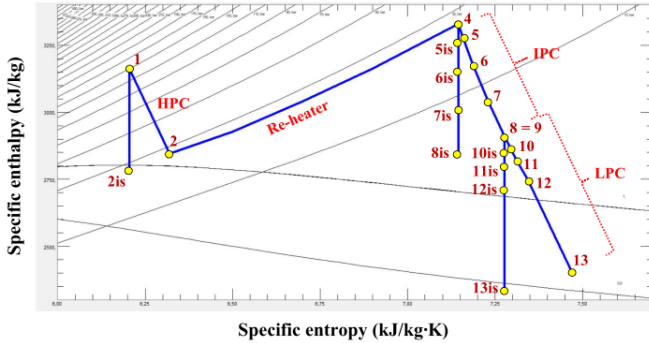


Fig. 2. Specific enthalpy – Specific entropy (*h-s*) diagram of real (polytropic) and ideal (isentropic) steam expansion process through each cylinder of the observed turbine

IPC

$$P_{re,IPC} = \dot{m}_4 \cdot (h_4 - h_5) + (\dot{m}_4 - \dot{m}_5) \cdot (h_5 - h_6) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6 - \dot{m}_7) \cdot (h_7 - h_8) \quad (3)$$

$$P_{id,IPC} = \dot{m}_4 \cdot (h_4 - h_{5is}) + (\dot{m}_4 - \dot{m}_5) \cdot (h_{5is} - h_{6is}) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6) \cdot (h_{6is} - h_{7is}) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6 - \dot{m}_7) \cdot (h_{7is} - h_{8is}) \quad (4)$$

LPC

$$P_{re,LPC} = \dot{m}_9 \cdot (h_9 - h_{10}) + (\dot{m}_9 - \dot{m}_{10}) \cdot (h_{10} - h_{11}) + (\dot{m}_9 - \dot{m}_{10} - \dot{m}_{11}) \cdot (h_{11} - h_{12}) + (\dot{m}_9 - \dot{m}_{10} - \dot{m}_{11} - \dot{m}_{12}) \cdot (h_{12} - h_{13}) \quad (5)$$

$$P_{id,LPC} = \dot{m}_9 \cdot (h_9 - h_{10is}) + (\dot{m}_9 - \dot{m}_{10}) \cdot (h_{10is} - h_{11is}) + (\dot{m}_9 - \dot{m}_{10} - \dot{m}_{11}) \cdot (h_{11is} - h_{12is}) + (\dot{m}_9 - \dot{m}_{10} - \dot{m}_{11} - \dot{m}_{12}) \cdot (h_{12is} - h_{13is}) \quad (6)$$

WT (Whole Turbine)

$$P_{re,WT} = P_{re,HPC} + P_{re,IPC} + P_{re,LPC} \quad (7)$$

$$P_{id,WT} = P_{id,HPC} + P_{id,IPC} + P_{id,LPC} \quad (8)$$

The isentropic loss of each cylinder and whole turbine is calculated according to the equation:

$$IS_{L,(i)} = P_{id,(i)} - P_{re,(i)} \quad (9)$$

while isentropic efficiency (again of each cylinder and whole turbine) is calculated by using an equation:

$$\eta_{IS,(i)} = \frac{P_{re,(i)}}{P_{id,(i)}} \quad (10)$$

In Eq. 9 and Eq. 10 index *i* is related to each turbine cylinder and to whole turbine (*i* = HPC; IPC; LPC; WT).

4. Steam operating parameters

Steam operating parameters of the real (polytropic) steam expansion process, which are obtained by the measurements during the turbine exploitation, are found in [18] and presented in Table 1. Other steam operating parameters presented in Table 1 which are not found in the literature, are calculated from known data in each operating point by using NIST-REFPROP 9.0 software [30].

Parameters of the ideal (isentropic) steam expansion process in each cylinder of the observed turbine are obtained by the calculations, according to previously described procedure, Fig. 2. Along with steam mass flow rates, in ideal (isentropic) mechanical power calculation the most important steam parameters are isentropic specific enthalpies, which are presented for each cylinder of the observed turbine in Table 2.

Table 1. Steam operating parameters required for the isentropic analysis of the observed steam turbine and each turbine cylinder – real (polytropic) steam expansion process

O. P. *	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality
1	440.0	130.00	90.20	3162.2	6.2047	Sh.**
2	240.5	26.50	88.22	2845.8	6.3190	Sh.

3. Isentropic analysis equations

Isentropic analysis of any steam turbine is actually a comparison of mechanical power developed during the real (polytropic) steam expansion process and mechanical power developed during the ideal (isentropic) steam expansion process. Ideal (isentropic) steam expansion process is theoretical one and it can be obtained if all the losses are neglected [26].

Isentropic analysis is a “black box” method because the inner structure of the whole turbine and each turbine cylinder is not known and it is not required. The required elements for this kind of analysis are all fluid flow streams to and from the observed component [27].

All equations presented in this section are related to turbine operating points presented in Fig. 1 and Fig. 2. Equations used in the isentropic analysis are composed according to the recommendations from the literature [28, 29]. Developed mechanical power (both real and ideal) of each cylinder and whole turbine are calculated according to the following equations:

HPC

$$P_{re,HPC} = \dot{m}_1 \cdot (h_1 - h_2) \quad (1)$$

$$P_{id,HPC} = \dot{m}_1 \cdot (h_1 - h_{2is}) \quad (2)$$

3	240.5	26.50	1.98	2845.8	6.3190	Sh.
4	440.0	25.00	88.22	3329.3	7.1458	Sh.
5	415.2	20.83	3.38	3280.5	7.1581	Sh.
6	360.8	13.66	3.88	3174.1	7.1872	Sh.
7	290.8	7.52	3.76	3038.7	7.2306	Sh.
8	224.4	4.00	0.92	2911.7	7.2770	Sh.
9	224.4	4.00	76.28	2911.7	7.2770	Sh.
10	206.4	3.33	1.40	2877.5	7.2901	Sh.
11	178.6	2.48	1.90	2824.7	7.3106	Sh.
12	138.7	1.57	7.15	2749.3	7.3436	Sh.
13	51.03	0.13	65.83	2402.8	7.4698	0.92

* O. P. = Operating Point (in accordance to Fig. 1)

** Sh. = Superheated

Table 2. Steam operating parameters required for the isentropic analysis of the observed steam turbine and each turbine cylinder – ideal (isentropic) steam expansion process

O. P. *	Pressure (bar)	Isentropic specific enthalpy (kJ/kg)
1	130.00	3162.2
2is	26.50	2788.1
3	26.50	-
4	25.00	3329.3
5is	20.83	3272.0
6is	13.66	3148.1
7is	7.52	2991.9
8is	4.00	2848.5
9	4.00	2911.7
10is	3.33	2871.2
11is	2.48	2809.7
12is	1.57	2722.3
13is	0.13	2340.3

* O. P. = Operating Point (in accordance to Fig. 2)

5. Results and discussion

Ideal (isentropic) and real (polytropic) mechanical power of each cylinder and whole analyzed turbine are presented in Fig. 3.

From Fig. 3 is clear that for each cylinder and whole turbine ideal (isentropic) mechanical power is higher than real (polytropic) one due to neglecting all losses which occur in the real steam expansion process. Observing all cylinders, it can be concluded that the dominant mechanical power producer is LPC which produces real mechanical power equal to 34875.23 kW. However, real mechanical power produced in LPC is only slightly higher than real mechanical power produced in IPC (which is equal to 34098.50 kW). The lowest real mechanical power is produced in HPC (28539.28 kW), which is notably lower in comparison to both IPC and LPC.

Whole observed steam turbine (WT) produces real mechanical power equal to 97513 kW, while its potential in mechanical power production (in ideal, isentropic scenario) is equal to 112246.91 kW. Whole turbine will never be able to produce ideal (isentropic) mechanical power in real exploitation, but ideal mechanical power can be used as a guideline (not only for the whole turbine, but also for each cylinder) for any improvements.

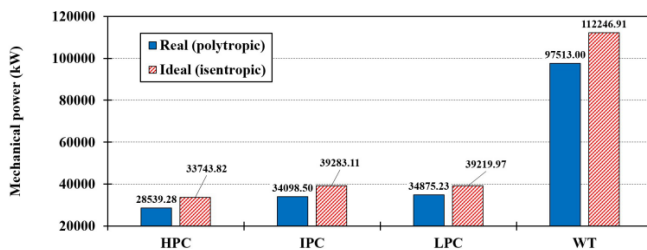


Fig. 3. Ideal (isentropic) and real (polytropic) mechanical power of each cylinder and whole analyzed turbine

Isentropic losses of each turbine cylinder and whole observed turbine are presented in Fig. 4.

Observing turbine cylinders, from Fig. 4 can be seen interesting fact related to this steam turbine – LPC which produces the highest real mechanical power has the lowest isentropic loss of all cylinders equal to 4344.75 kW, while HPC which produces the lowest real mechanical power has the highest isentropic loss of all cylinders equal to 5204.54 kW. It is also interesting that IPC which real mechanical power is very close to one produced in LPC has isentropic loss only slightly lower than HPC (IPC isentropic loss is equal to 5184.62 kW), Fig. 3 and Fig. 4.

Isentropic loss of the whole observed steam turbine is equal to 14733.90 kW.

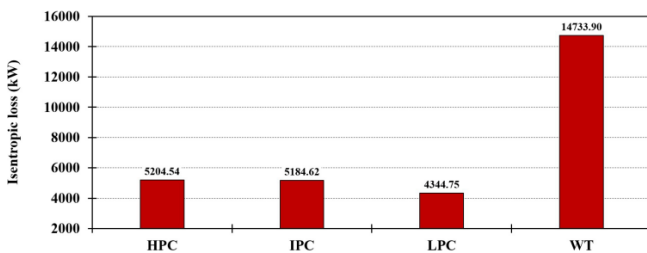


Fig. 4. Isentropic loss of each cylinder and whole analyzed turbine

Isentropic efficiencies of each cylinder and whole observed steam turbine are presented in Fig. 5.

By observing results related to all three cylinders, it can be concluded that isentropic losses, Fig. 4, and isentropic efficiencies, Fig. 5, are reverse proportional, because the cylinder with the lowest isentropic loss (LPC) has the highest isentropic efficiency equal to 88.92%, while the cylinder with the highest isentropic loss (HPC) has simultaneously the lowest isentropic efficiency equal to 84.58%. Surprisingly, isentropic efficiency of the IPC is equal to 86.80%, which is higher in comparison to HPC but simultaneously lower than LPC. Finally, isentropic efficiency of the whole analyzed steam turbine is equal to 86.87%.

In the literature can be found many comparisons of a various steam turbines. Observing literature [31], it can be stated that this steam turbine shows some differences related to isentropic performance in comparison to the steam turbines from marine, conventional and ultra-supercritical steam power plants. For steam turbine analyzed in this paper can be seen that LPC has higher isentropic efficiency in comparison to IPC, while for other comparable steam turbines IPC has notably higher isentropic efficiencies than both HPC and LPC. Also, while observing isentropic efficiencies of all cylinders and whole steam turbine analyzed in this paper, it can be concluded that they show isentropic performance very close to the turbine from the conventional steam power plant. Obtained isentropic efficiencies of the cylinders and whole turbine in this analysis are higher in comparison to steam turbine from marine propulsion steam power plant, but still lower in comparison to steam turbine from ultra-supercritical power plant.

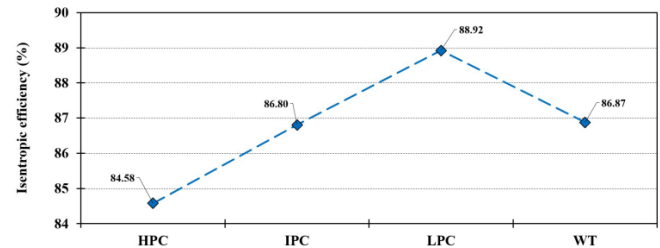


Fig. 5. Isentropic efficiency of each cylinder and whole analyzed turbine

Further analysis of this steam turbine will be based on the investigation of its improvement possibilities and possible optimization (for each cylinder and whole turbine) using various conventional [32] and machine learning methods and techniques which are often used for similar kind of problems [33-36].

6. Conclusions

In this paper is presented an isentropic analysis of a steam turbine and each of three turbine cylinders from Municipal Solid Waste (MSW) power plant. Obtained results lead to several interesting conclusions:

- The dominant mechanical power producer in the observed turbine is LPC which produces real mechanical power equal to 34875.23 kW. Whole observed steam turbine produces real mechanical power equal to 97513 kW.
- LPC which produces the highest real mechanical power has the lowest isentropic loss of all cylinders equal to 4344.75 kW, while HPC which produces the lowest real mechanical power has the highest isentropic loss of all cylinders equal to 5204.54 kW.
- Isentropic losses and isentropic efficiencies are reverse proportional, because the cylinder with the lowest isentropic loss (LPC) has the highest isentropic efficiency equal to 88.92%, while the cylinder with the highest isentropic loss (HPC) has the lowest isentropic efficiency equal to 84.58%.
- Surprisingly, isentropic efficiency of the IPC is equal to 86.80%, which is higher in comparison to HPC but notably lower than LPC. The isentropic efficiency of the whole analyzed steam turbine is equal to 86.87%.
- For the steam turbine analyzed in this paper can be seen that LPC has higher isentropic efficiency in comparison to IPC, while for other comparable steam turbines from the literature IPC has notably higher isentropic efficiencies than both HPC and LPC.
- Isentropic performance of the observed steam turbine and its cylinders is very close to the turbines from conventional steam power plants. Obtained isentropic efficiencies of the turbine and cylinders in this analysis are higher in comparison to steam turbines from marine propulsion power plants, but still lower in comparison to steam turbines from ultra-supercritical power plants.

7. Acknowledgment

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Mechanical characterisation of Babbitt Alloys solidified under different conditions

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Abstract: This paper investigates the mechanical behaviour of SnSb11Cu6 Babbitt alloys solidified under pressure and under atmospheric conditions. Quasi-static tests were performed at three different constant strain rates: 0.001 s^{-1} , 0.003 s^{-1} , and 0.01 s^{-1} , while dynamic tests were conducted at strain rates corresponding to impact speeds of 10 m/s and 20 m/s. The results indicate that alloys solidified under atmospheric conditions exhibit higher compressive strength in the quasi-static regime than those solidified under pressure. However, as the impact speed increases to 1400 s^{-1} the compressive strength of both materials converges. Beyond this rate (up to 2800 s^{-1}), the alloy solidified under pressure shows a slight performance shift, suggesting better property stability at higher loading rates. Overall, the alloy solidified under atmospheric conditions offers superior performance for low-strain applications, whereas the alloy solidified under pressure demonstrates more stable properties under high-strain loadings. These findings offer valuable insights for the selection and design of materials in tribological systems, particularly where performance varies under different loading conditions.

Keywords: SnSb11Cu6 ALLOY, BABBITT, COMPRESSIVE STRENGTH, HIGH STRAIN RATE PERFORMANCE

1. Introduction

Babbitt alloys are bearing materials with good anti-friction, corrosion and wear resistance properties, which makes them widely used in different industries [1,2]. The tin-based Babbitt is based on Sn with a small amount of Sb and Cu and is used for bearing bushes of ships, internal combustion engine spindles, large mechanical main shafts and connecting rod bearings [1-3]. To improve further their properties different approaches are involved including modification of the microstructure by adding alloying elements such as Cd, Pb, Ni, As, Ag, Zn, Ti, Co and oxides [1,3-7], by controlling the crystallisation rate via different production techniques [7-15] and thermo-plastic treatment processes such as die forging and friction stir processing [16 - 20]. Generally, it is considered that Tin Babbitt is a multi-phase alloy consisting of α -phase (solid solution of Sn, Cu, and Sb), β -phase (Sn-Sb compound), η -phase (Cu_6Sn_5 compound), ϵ -phase (Cu_3Sn compound), γ -phase ($\text{Cu}_{31}\text{Sn}_8$ compound) and Cu_2Sb phase [13]. With Sb content over 10%, Tin Babbitt is classified as a casting alloy with microstructure most often constituting of the three-phase form: α (soft and ductile matrix, solution of antimony and copper in tin), β (angular crystals of the SnSb phase), η (acicular precipitates of the Cu_6Sn_5 phase) [17,18,20]. The metallographic analysis has proved that the black matrix is α phase (α solid solution of Sb dissolved in Sn), the bright block triangle or square crystals are β phase (SnSb), and the white dotted, needle-like or star-shaped crystals are eta phase (Cu_6Sn_5) [1,2]. The Cu_6Sn_5 crystal possesses the highest deformation resistance and stiffness, followed by SnSb and β -Sn. SnSb crystal shows the best plasticity, followed by β -Sn and Cu_6Sn_5 because β -Sn and SnSb are plastic materials, and Cu_6Sn_5 is brittle [2]. It is determined that an increase in the solidification rate (rapid cooling) leads to the formation of a structure with reduced-in-size intermetallic particles uniformly distributed in the matrix phase, which leads to enhanced mechanical properties [9,12] while decreasing the solidification rate results in coarser microstructure. It can be concluded that the dispersion of secondary phase particles seems to be an effective mechanism for strengthening tin alloys for sliding bearings [13,20]. The solidification process could be the key to managing the mechanical properties of Babbitt alloys.

However, there is a lack of research in the literature investigating the mechanical behaviour of SnSb11Cu6 Babbitt alloys solidified under different conditions, specifically using quasi-static and dynamic compressive tests, leaving a gap in understanding their performance under varying loading scenarios.

This study aims to comprehensively evaluate the mechanical behaviour of SnSb11Cu6 Babbitt alloys solidified under atmospheric conditions and under pressure, focusing on how these solidification methods influence their strength and stability under different compressive loading conditions. To assess the compressive strength, the alloys will undergo quasi-static and dynamic

compressive tests, enabling the evaluation of their suitability for applications requiring varied strain-rate performance.

2. Materials and methods

Both SnSb11Cu6 alloys were prepared through controlled melting and solidification processes. The first alloy (BMinf) underwent solidification under pressure, where the molten metal was poured at 440°C into a preheated mould and solidified under a pressure of 80 MPa for 60 seconds. Following the solidification under pressure, the alloy was allowed to cool naturally at room temperature. The second alloy (BMat) was directly poured into a die and cooled at room temperature without applying external pressure. This approach resulted in two distinct solidification conditions, allowing for a comparative analysis of their mechanical behaviour under different loading regimes.

The mechanical properties of the Babbitt alloys under quasi-static compression were determined by a universal servo-hydraulic testing machine Zwick-Roell HA250. Experiments were carried out at three compression strain rates - 0.001 s^{-1} , 0.003 s^{-1} and 0.01 s^{-1} , all referred to ISO 13314 standard for quasi-static compression testing range. Specimens with cylindrical $\text{Ø}10\times15\text{mm}$ cross-sections were prepared with a length-to-diameter ratio between 1 and 2. The dynamic compression tests were conducted by a modified Split Hopkinson Pressure Bar (SHPB) apparatus, designed for impact testing of porous and light materials, at strain rates of about $\sim 1400\text{ s}^{-1}$ and $\sim 2800\text{ s}^{-1}$, corresponding to impact speeds of about 10 m/s and 20 m/s. The specimens used to determine the dynamic properties of the fabricated materials are cylindrical with a diameter of 8 mm and a height of 8 mm.

3. Results and discussion

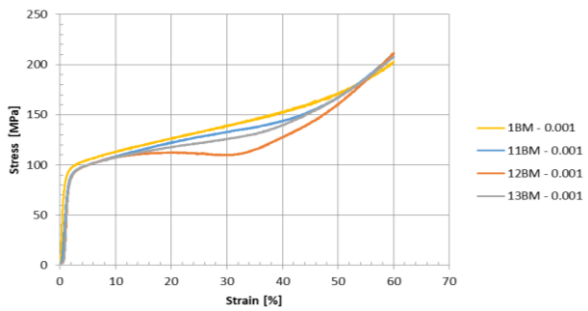
The mechanical properties of the Babbitt alloys tested under quasi-static loadings are summarised in Table 1. The best results for both materials are achieved at the strain rate of 0.01/s, followed by the results at 0.003/s and the lowest compressive strength is obtained at a strain rate of 0.001/s. When comparing the two materials at the same testing speed it is obvious that the SnSb11Cu6 materials crystallised under atmospheric conditions possess better compression strength than those crystallised under pressure. It is in good correspondence with the findings that rapid cooling inhibits the formation and growth of hard cuboid SbSn crystals and strongly influences (increases) mechanical behaviour, wear resistance and hardness [13]. Except for the β -phase, the rapidly cooled Babbitt exhibits a fine Cu-Sn compound and has higher fatigue strength than slowly cooled innings [13].

Quasi-static compression test results are presented in Fig. 1 for SnSb11Cu6 materials crystallised under pressure and in Fig. 2 for SnSb11Cu6 materials crystallised under atmospheric conditions.

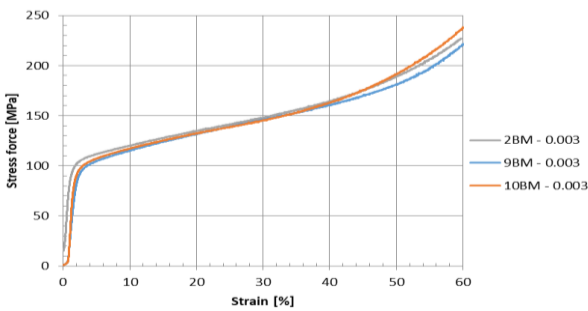
Table 1: Average values of the mechanical properties of tested materials.

Specimens		E GPa	YS MPa	Compressive strength, MPa
BMat, 0.01 s^{-1}	Average	9.8	88.8	292.0
	SD	2.4	4.5	6.1
BMat, 0.003 s^{-1}	Average	8.9	84.1	264.1
	SD	1.9	3.1	2.3
BMat, 0.001 s^{-1}	Average	7.9	76.9	232.3
	SD	2.8	4.2	6.6
BMinf, 0.01 s^{-1}	Average	10.6	85.8	255.2
	SD	0.5	3.8	5.6
BMinf, 0.003 s^{-1}	Average	9.4	84.8	228.9
	SD	2.5	3.8	8.5
BMinf, 0.001 s^{-1}	Average	11.0	80.3	208.6
	SD	2.2	1.2	4.0

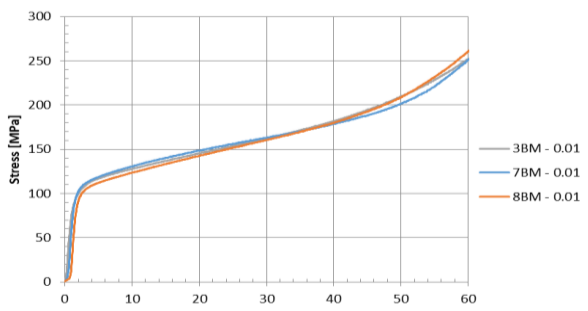
Almost all curves exhibit consistent behaviour under quasi-static compression. The only difference is a result of the change in testing speeds. It is again obvious, that the increase in compression speed leads to an increase in the compressive strength. The results indicate that SnSb11Cu6 materials crystallised under atmospheric conditions possess better compression strength under quasi-static loadings than the ones crystallised under pressure for all the quasi-static testing speeds. The curves are smooth, without any fluctuations. The average stress-strain diagrams of the six tested series are summarised in Fig. 3.



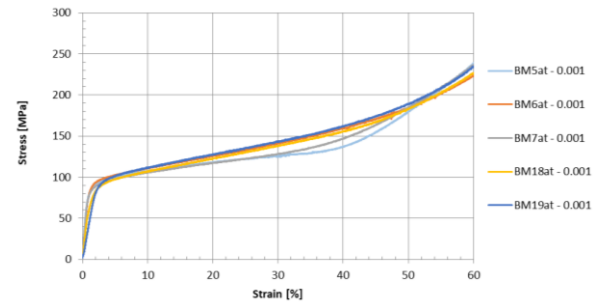
a)



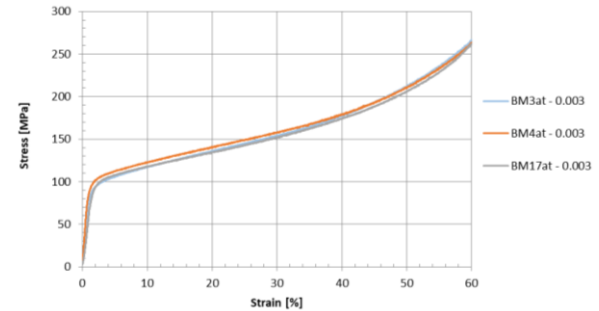
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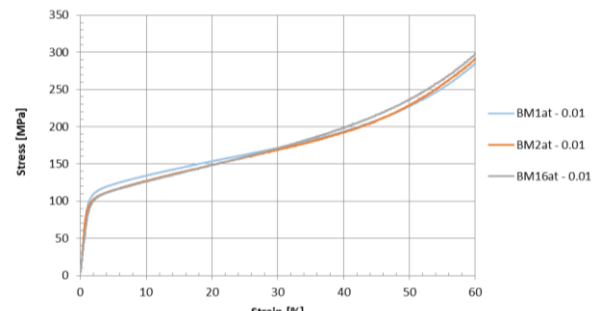
c)

Fig. 1 Quasi-static test results of SnSb11Cu6, crystallised under pressure a) strain rate 0.001 s^{-1} ; b) strain rate 0.003 s^{-1} ; c) strain rate 0.01 s^{-1} .

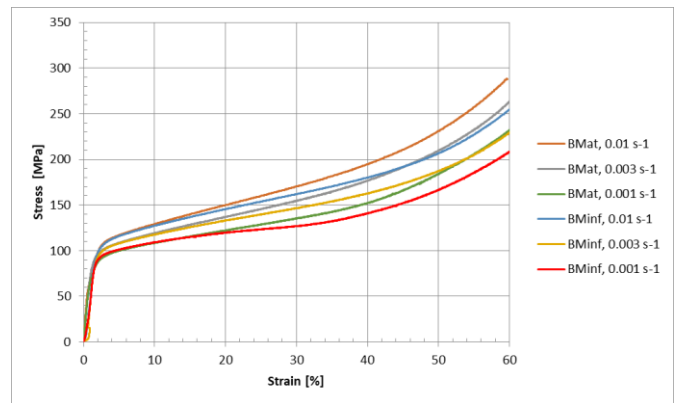
a)



b)



c)

Fig. 2 Quasi-static tests result of SnSb11Cu6, crystallised under atmospheric conditions: a) strain rate 0.001 s^{-1} ; b) strain rate 0.003 s^{-1} ; c) strain rate 0.01 s^{-1} .**Fig. 3** Comparison of average quasi-static test results of SnSb11Cu6

After 35% deformation all solidified under pressure specimens showed some barrel-shaped deformation, although more serious failure behaviours were observed only at testing speeds of 0.001 s^{-1} . The first formation of visible by naked-eye shear cracks is after 33-37 % deformation (in specimens tested at 0.001 s^{-1} and 0.003 s^{-1}) and at 53% deformation for strain rates of 0.01 s^{-1} . The crushing stages of different specimens are presented in Table 2. Specimens 11, 10 and 8 are solidified under pressure and tested at strain rates 0.001 s^{-1} , 0.003 s^{-1} and 0.01 s^{-1} respectively. Specimens 5, 3 and 2 are solidified at atmospheric conditions and again tested at strain rates 0.001 s^{-1} , 0.003 s^{-1} and 0.01 s^{-1} . Babbitt alloys solidified at

atmospheric conditions demonstrate higher plasticity and some cracking is only observed at the lower testing speed.

Table 2: Actual crushing characteristics at different strains

$\varepsilon, \%$	20%	30%	40%	50%	60%
11BMinf 0.001 s ⁻¹					
10BMinf 0.003 s ⁻¹					
8BMinf 0.01 s ⁻¹					
5BMat 0.001 s ⁻¹					
3BMat 0.003 s ⁻¹					
2BMat 0.01 s ⁻¹					

The dynamic compression tests of both materials are performed at moderate strain rates of 1400 s⁻¹ and high strain rates of 2800 s⁻¹. The results from dynamic tests of SnSb11Cu6 materials crystallised under pressure (BMinf) and under atmospheric conditions (BMat) are shown in Fig. 4 and Fig. 5 respectively. The average values of the mechanical characteristics are listed in Table 3.

Table 3: Average values of the mechanical properties of tested materials.

Specimens		E GPa	YS MPa	Compressive strength, MPa
BMat, 11 m/s	Average	27.1	125	287
	SD	4.2	7	7
BMat, 20 m/s	Average	14.7	103	262
	SD	2.1	13	41
BMinf, 11 m/s	Average	20.5	100	284
	SD	4.3	17	16
BMinf, 20 m/s	Average	10.2	89	300
	SD	1.1	30	10

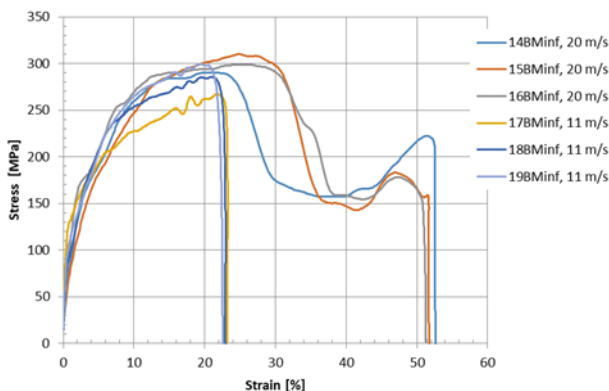


Fig. 4 SHPB dynamic test results of SnSb11Cu6, crystallised under pressure.

The stress-strain curves (fig.4) under dynamic compression of solidified under pressure (BMinf) material revealed quite close characteristics up to the yield strength. The ultimate strength

slightly increased with the strain rate. More pronounced is the strain rate effect over the deformation occurrence before critical fracture - up to 23% at strain rates of 1400 s⁻¹ and up to 32% at strain rates of 2800 s⁻¹. Figure 5 shows the results of dynamic tests of SnSb11Cu6, crystallised under atmospheric conditions. The resulting curves from the dynamic tests of BMat specimens consist of much more fluctuations than BMinf material. The type of failure demonstrated in specimens at strain rates of 1400 s⁻¹ is a plastic failure, while a smash failure is observed at strain rates of 2800 s⁻¹. Specimens that showed the lowest compression strength (specimens 14BMinf, 13BMat and 14BMat) demonstrated dissimilar amounts of splitting failure before the final smash failure occurred. Tested specimens at different strain rates before and after tests are presented in Table 4.

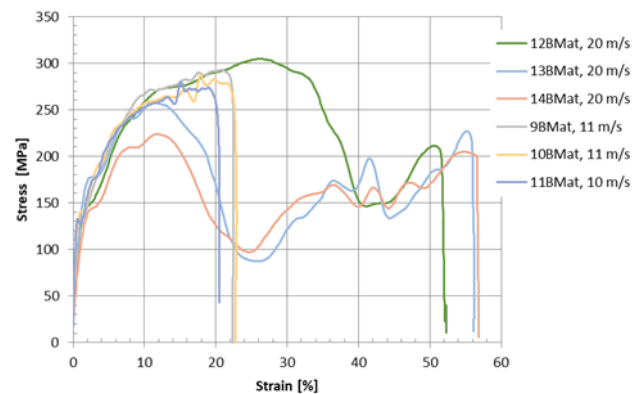


Fig. 5 SHPB dynamic test results of SnSb11Cu6, crystallised under atmospheric conditions.

Table 4: Tested specimens before and after tests at different strain rates.

Strain rate	crystallised under pressure		under atmospheric conditions	
	before	after	before	after
0.001				
0.003				
0.01				
1400				
2800				

In our case, all tested at 1400 s⁻¹ specimens exhibited plastic failure, while at some tested at 2800 s⁻¹ partial splitting was observed. The observation of average stress-strain diagrams revealed quite a similar compression strength at both strain rates, except for the BMat specimens at a strain rate of 2800 s⁻¹ (fig.6).

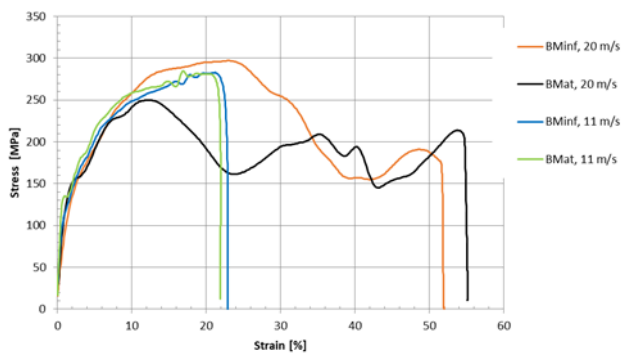


Fig. 6 Comparison of average SHPB dynamic test results of all tested SnSb11Cu6 materials.

A comparison of all tested samples at all tested strain rates is shown in Fig. 7. It can be seen that the compressive strength of crystallised under atmospheric conditions Babbitt material (fig. 7a) ranges in the interval of 225–300 MPa and thus makes it quite independent of strain rate in the interval $0.001\text{--}2800\text{ s}^{-1}$. The situation with solidified under pressure Babbitt (fig. 7b) is similar with strength between 205–310 MPa in the strain rate interval $0.001\text{--}2800\text{ s}^{-1}$. The specimens displayed almost no change in the elastic stage, with elastic modulus between 8–27 GPa in the whole range of strain rate testing. The yield strength at high strain rates is 90–125 MPa and 75–90 MPa under quasi-static loadings. Generally, yield and ultimate strengths increased slightly with strain rate, which is more evident in solidified after infiltration under pressure Babbitt.

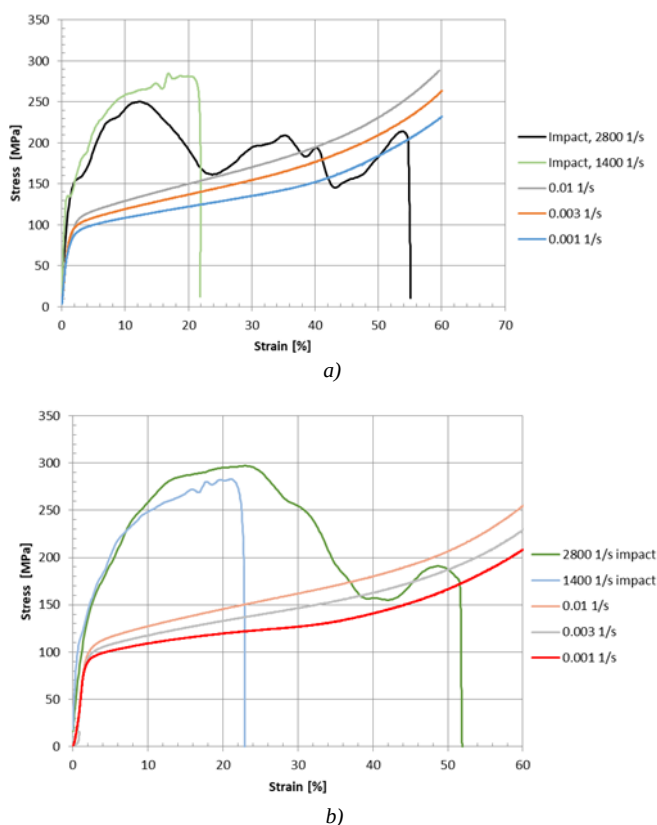


Fig. 7 Comparison of average results of SnSb11Cu6 materials: a) Babbitt material crystallised under atmospheric conditions; b) Babbitt material solidified under pressure.

4. Conclusions

The current investigation focuses on the mechanical behaviour of two Babbitt materials, solidified under different conditions and

tested under quasi-static and high-strain compressive loading conditions. The major conclusions that could be drawn back are:

1. Alloys solidified under atmospheric conditions exhibit higher compressive strength in the quasi-static regime than those crystallised under pressure.
2. When the impact speed increases to 1400 s^{-1} the compressive strength of both materials converges.
3. After further increase in the strain rate (up to 2800 s^{-1}), the alloy crystallised under pressure shows a slight performance shift, suggesting better property stability at higher loading rates.
4. Generally, the alloy solidified under atmospheric conditions offers superior performance for low-strain applications, whereas the crystallised under pressure alloy demonstrates more stable properties under high-strain loadings.

5. Acknowledgments

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6. Funding

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Augmented Analytics platform and Service 4.0 solution for service excellence

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Abstract: In the modern era, it is a challenge to develop a high-quality business product that adequately serves its real purpose, by implementing Machine Learning (ML) and Large Language Models (LLM), both generally defined as AI. For this reason, Danlex 78 proposes a multilayer approach for developing an augmented analytics platform and Service 4.0 solution to accomplish service excellence in x-ray inspection systems. In this approach, AI is important, but still just a tool for achieving targeted business goals. The complex ecosystem of business knowledge combined with science and technology leads to our working solution. This article presents our approach and marks the most important KPIs for achieving service excellence in X-ray inspection systems maintenance.

Keywords: X-RAY SYSTEM, REMOTE DIAGNOSTICS, PREDICTIVE MAINTENANCE, SERVICE EXCELLENCE, BI DASHBOARD

1. Introduction

The current state-of-the-art maintenance of X-Ray Security Systems is a costly "run it until it breaks" reactive maintenance approach resulting in downtime, high equipment lifecycle costs, and costly large stockpiles of spare parts. The maintenance costs of an X-Ray System during its lifecycle often exceed 100% of the System's purchase price, thus greatly increasing its TCO.

Predictive maintenance is a powerful technology that is well known in various industries [1]. But even today, there are still some industries where there's no evidence that predictive maintenance is being used at all. This is certainly the case in the X-ray security screening industry. These complex electromechanical systems are widely used for X-ray inspection in airports, border control and other security applications. As with any other critical infrastructure, the performance and health status of the X-ray screening system must be constantly monitored and subject to analysis to achieve a flawless workflow and prevent unexpected failures.

With almost 30 years' experience of installing, servicing, and maintaining large numbers of X-ray systems, the Danlex engineering team was faced with the undeniable need for predictive maintenance solutions a long time ago. But at the time, no X-ray manufacturer or third-party company had a solution that came close to what we needed. So, with unwavering resolve, we set out to develop our own predictive maintenance solution eight years ago. The result was the development of our Predictive Maintenance for Non-Intrusive Inspection Systems (PMT4NIISTM).

Over the years, PMT4NIIS has been installed and tested on dozens of X-ray screening systems. Working in the field with real cases and solving real problems, we have encountered obstacles that we had not foreseen. All this experience has helped to drive our development, following a scientific and engineering approach [1, 2]. During this time, PMT4NIIS has proven to be a turnkey solution that offers ease of use, reliability, and customization to seamlessly meet customer requirements.

With years of experience in servicing X-Ray Security Systems, the Bulgarian technology and service provider Danlex is tackling these challenges with the PMT4NIIS solution designed exclusively for the X-Ray Security Systems manufactured by Smiths Detection.

PMT4NIIS is a predictive maintenance tool and an augmented analytics platform and Service 4.0 solution, set to transform the way X-Ray Security Systems are maintained and serviced.

As a remote asset management tool, it combines Industrial IoT with proprietary software, powered by AI and Machine Learning algorithms, to keep X-Ray Systems operational. PMT4NIIS offers real-time monitoring with automatic early-warning alerts, a 24/7 Service Desk, a Business Intelligence (BI) Dashboard, and a professional knowledge base for troubleshooting, thus elevating maintenance standards to service excellence.

Now PMT4NIIS has evolved into PM4X LPRTM (Predictive Maintenance for X-ray systems – Longevity, Predictability and Reliability) with new and enhanced features.

2. How PM4X LPRTM works?

The near real-time advanced sensor telemetry combined with statistical, AI, and ML algorithms, PM4X LPR transforms the traditional reactive maintenance approach into a new proactive AI-driven maintenance tool. It provides the service specialist large amount of data in a structured BI Dashboard, including:

- Real-time status of the technical health of the X-Ray system
- Real-time values of the system's key performance indicators
- Historical data overview to identify patterns in the deterioration of the X-ray system overtime
- Real-time results from the Condition-based and Predictive models
- Automatic alert notification system.

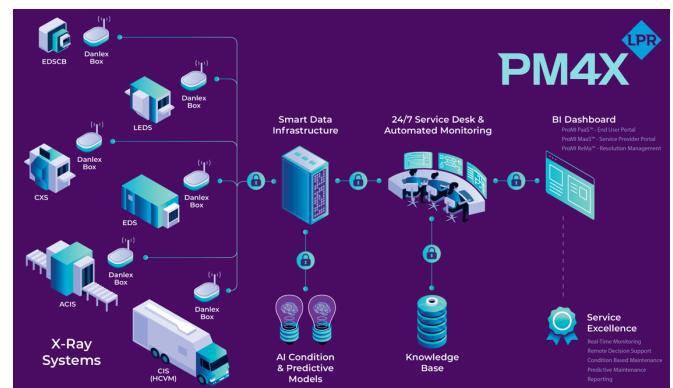


Fig. 1 PM4X LPR infrastructure for remote monitoring

3. Proactive Maintenance

Condition-based maintenance (CBM) and Predictive Maintenance (PdM) are modern approach to equipment maintenance that relies on continuous monitoring and assessment of asset condition in real-time or at specified intervals. Unlike traditional maintenance methods, which are based on fixed periods for replacement or repair, CBM and PdM utilizes data collected from sensors to detect potential failures and optimize maintenance. This means that repairs and replacements are performed only when necessary, saving time and resources.

CBM and PdM monitors key environmental parameters such as temperature and humidity, as well as equipment-specific characteristics like electrical signals and other indicators that provide information on the technical condition of the equipment.



Fig. 2 DanlexBox: Proprietary edge device for real-time sensor data transfer

Continuous reliable operation is of utmost importance for X-ray security systems used at airports, borders, and critical infrastructure. The application of the CBM and PdM approach enables the timely detection of potential malfunctions, preventing unwanted interruptions and system downtime. This ensures high operational efficiency.

The main advantages of proactive maintenance include:

- Improved maintenance planning – maintenance is performed only when necessary, minimizing unplanned downtime.
- Prolonged equipment lifespan – early detection of faults allows for quicker response and prevents serious damage.
- Reduced maintenance costs – Maintenance becomes more efficient, avoiding unnecessary interventions.

The proactive maintenance is an essential part of the predictive maintenance philosophy and Service 4.0, based on advanced IoT technologies and analytics for intelligent asset management.

To support this, we developed DanlexBox – an autonomous IoT device for optimal monitoring.

DanlexBox is a multi-component electronic device developed by Danlex' R&D team. Its main functionality is to collect and transmit telemetry data to the PM4X Smart Data Infrastructure, even after a power outage.

DanlexBox ensures reliable monitoring of environmental parameters, electrical parameters, and the temperature of X-ray generators in systems such as CXS and EDS.

4. Connectivity and Security



Fig. 3 Connectivity to the PM4X Infrastructure

To meet the ever-increasing demands for information and cyber security, all data collected by PM4X LPR is transmitted via encrypted channels to a secure data center.

Equipped with the latest Intrusion Prevention Systems (IPS) and Intrusion Detection Systems (IDS), we protect the entire infrastructure and data from unattended access and secure the devices against external threats.

5. The Key to Cost Savings and Availability

The potential impact of PM4X LPR on the X-Ray security industry is significant. By reducing unplanned downtime and maintenance costs, and increasing system availability, this technology is poised to enhance asset Key Performance Indicators (KPIs) for all stakeholders by providing:

- High Equipment Availability
- Equipment Effectiveness
- Optimised Equipment Utilization
- Reduced Maintenance Costs
- Data-Driven Insights
- Digital and Green Transitions



Fig. 4 PM4X LPR Asset Management Platform

6. The value propositions for the end users

The scope of PM4X LPR is extensive and caters to a wide range of industries and organisations, including:

- **Airports:** Ensuring fast turnaround times
- **Cargo Companies:** Avoiding deconsolidation of shipments
- **Express Cargo Industry:** Enabling fast security inspections
- **Ports:** Securing global trade and e-commerce
- **Customs:** Enhancing customs control while facilitating trade
- **Border Control:** Ensuring national security and public safety
- **Freight Forwarders:** Optimising security inspection processes to expedite shipments

- **Security Organisations:** Providing robust tools for law enforcement bodies and security agencies
- **Governmental establishments:** Enhancing the level of security

The introduction of PM4X LPR predictive maintenance solution is a significant leap forward in the quest for enhanced security. This innovative solution not only offers cost savings and efficiency but also ensures business continuity and smoothness of operations.

As technology continues to evolve, so too will the ways we safeguard our environments. Predictive maintenance is at the forefront of this evolution, contributing to the creation of a safer and more secure future environment.

7. Results and discussion

The adoption of CBM and PdM for non-medical X-ray systems can significantly improve operational efficiency and service excellence through remote diagnostics for faster problem resolution.

One of the most powerful benefits of a proactive maintenance approach is the ability to perform remote diagnostics, allowing maintenance teams to identify problems before failure occurs, without the need for on-site interventions. This leads to a significant reduction in on-site service calls, resulting in lower travel costs and reduced downtime. Real-time system monitoring provides instant alerts for abnormal parameters such as tube degradation, cooling system inefficiencies or voltage fluctuations. BI Dashboard analysis tools allow technicians to troubleshoot issues remotely, minimising the need for emergency interventions.

By moving from traditional preventive maintenance to data-driven predictive models, organisations such as service providers have significantly reduced operational costs. For example, effective PdM strategies improve spare parts management by predicting which components are likely to fail and when, resulting in (i) a reduction in spare parts inventory costs, as service providers no longer need to overstock expensive X-ray components (e.g. high voltage generators, cooling units and X-ray tubes); (ii) just-in-time inventory management, preventing shortages and overstocks. This allows maintenance teams to pre-order the components they need before a failure occurs, eliminating delays caused by unexpected parts shortages.

8. Conclusions

CBM and PdM play a critical role in achieving service excellence by improving X-ray system reliability, reducing downtime, and optimising maintenance strategies. By using real-time data, advanced analytics, and predictive technologies, Service Providers can move from reactive to proactive maintenance approaches, improving operational efficiency and cost effectiveness. Implementing these maintenance strategies not only ensures equipment longevity but also enhances customer satisfaction by minimising disruptions and maintaining consistent service quality. As technology continues to evolve, the integration AI, IoT, and machine learning into CBM and PdM will further refine maintenance practices, driving continuous improvement in service excellence.

9. Acknowledgements

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Digital Transformation in Human Capital Management in Tourism

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Abstract: This report identifies the drivers and challenges of tourism human capital management under the conditions of ubiquitous digital transformation. Major attention was paid to integration of opportunities of the existing technologies caused by the penetration of artificial intelligence in all spheres of the tourism industry, while preserving the which will give way to harmonious interaction and will create technological intelligence.

Key words: DIGITALIZATION, HUMAN CAPITAL MANAGEMENT, TOURISM, CHALLENGES

1. Introduction

The topic of digital transformation in tourism is of utmost importance in the context of the rapidly changing competitive environment in the tourism industry. The digital transformation in the tourist industry is already a fact and this is understandable because the customer is a driving factor. This new digital environment is changing the existing stereotypes of work, which are not always applicable due to the fact that they do not always reflect the complexity of real competition in the tourism business, which is rapidly developing in parallel with digitalization. There is a growing need for modeling of thinking „re-design“ in the direction of adaptation to the continuous transformations in tourism. Through an objective analysis of the opportunities and challenges associated with digital technologies, the report aims to offer practical guidelines for combining technology with human capital in tourism, without claiming to be exhaustive.

2. Preconditions and Means for Resolving the Problem

The topic of the impact of digital transformations in tourism is extremely comprehensive. New technologies such as **artificial intelligence (AI)**, **the Internet of Things (IoT)**, **big data (Big Data)** and **virtual reality (VR)** - the drivers for sustainability, the adoption of digital technologies and skills shortages have challenged tourism business to rethink the transformational models of human capital management involving a combination of management practices related to stimulate and development of human potential and building and maintaining a culture of technological innovations. This problem will be theoretically and empirically investigated through a case study, using different research methodologies. The problem can be formulated as: **How will the New Technologies in the Face of Artificial Intelligence, Robots and Automation Change the Tourist Industry?**

3. Solution of the examined problem

The main **purpose** of this study is to explore and analyze how the implementation of new digital technologies is changing traditional approaches in tourism management, while exploring the impact on the human capital. The main issues and challenges associated with the use of thw twchnologies will be addressed, including the issue of job retention, the need for employee adaptation, and the risks of over-reliance on technology. Issues related to ethical challenges are touched upon, and in particular the **objectives** are related to: *firstly*, exploring the effect of digital transformation on the tourist industry and in particular how technologies are transforming tourism management; *secondly*, analyzing the role of human capital in the tourism sector, focusing on how the edge hand adapts to digital changes and *thirdly*, exploring the impact of new technologies in tourism by comparing the advantages and disadvantages, to formulate recommendations for tourism businesses on how to effectively integrate them with human capital in order to optimize productivity while maintaining customer satisfaction. The **subject of research** of this report is the interaction between human capital and digital technologies in tourism. The opportunities that new technologies provide will also be considered and the challenges related to the adaptation of human

capital and the need to manage these processes. The analysis aims to highlight how the symbiosis of technology and human contribution can ensure the sustainable development of the tourism sector. The **methodology** of the study encompasses the conceptual formulation of the problem under study through a review of the literature in this field and systematization of the theoretical positions of leading researchers and generalized personal experience of the specific aspects of digital transformation in tourism. The structure of the report includes the purpose of the study, field of study, studies, data processing, analysis of the results obtained.

Digital Transformation in Tourism

The digital and real worlds are increasingly merging and taking on the appearance of a technological revolution, covering all spheres of life. It is no coincidence that all new challenges are distinguished by the fact that they are caused by technological transformation, and in particular by digitalization and information technologies. Digital transformation is a process that affects all aspects of the tourism industry, encompassing both traditional services and innovative approaches to offering tourism products. New technologies are reshaping the way travel companies work and customers interact with them. This physically nonexistent environment created by information technology is about to transform the tourist industry. The leading technological innovations that have dramatically changed the face of tourism are external to the industry. Innovation and innovative strategies are becoming key for businesses. The digital transformation of the tourist industry has drastically changed the way tourism businesses operate, interact with customers, and provide services. At the heart of this transformation is the growing integration of artificial intelligence, which has the potential to revolutionize operational efficiency, improve personalization, and redefine the user experience. The impact of digitalization on tourism and threats and opportunities are illustrated on (Fig. 1).

IMPACT OF DIGITALIZATION ON TOURSISM		
OPPORTUNITIES AND THREATS FOR THE TOURISM INDUSTRY		
ADVANTAGES	DISADVANTAGES	INFLUENCE
Ability to perform detail-oriented tasks	Costly implementation	Internal organization
Accelerated processing of data	Need for expertise	Management
Saving labor	Talent shortage	Company image
Consistent results	Reinforcement bias	Workforce
Customer satisfaction	Lack of conviction	Clients contractors
Client personalization	Job closure	
Virtual agents available 24/7		
THE INTRODUCTION OF NEW TECHNOLOGIES WILL AFFECT A CERTAIN ASPECT OF TOURISM COMPANIES		

Fig. 1. Impact of Digitalization on Tourism

Digitalization offers technologies, approaches and tools that can add value to the tourist product. Digital transformation by creating new opportunities for tourism companies and introducing new tourist products and services, new business models and processes. Digital technologies will take advantage of the comfort and

information on the tourist site. At the same time, the human capital in the tourism sector can be replaced. [1]

The rapid entry of new technologies in tourism is a topic that has become relevant in the tourist industry, especially because it is related to the work of people. The digital transformation in tourism is not just an innovative process, but a necessity dictated by the dynamic exchange of consumers for consumers and the competitive onslaught in the sector. Tourist services, which are used for interaction and physical communication channels, which are increasingly predominating digital platforms and automated solutions. Human capital, which has traditionally been the basis of the tourism industry, is also undergoing transformation. Jobs that require routine and repetitive activities are most vulnerable to automation, while there is a growing need for staff with digital skills. This raises the question of retraining and adaptation of employees to the new requirements.

One of the main reasons to go digitalization is the customer. New technologies unconditionally accelerate the sales of the many diverse tourist products in tourism practice through the visualization and reliability of information about the tourist product in an attempt to overcome the intangible nature. Logically, the question arises: **Digital or Human era?** One discussion topic is the entry of robots into the field of tourism and job losses, causing a lot of controversy about the future trends in the development of tourism - **Robotization or Humanization?** Experts in tourism say that it is robots that can provide the highest quality service to visitors, maximally consistent with the requirements of accommodation establishments, and many countries in Europe, and not only, have relied on robots that serve visitors at the reception in a number of hotels. [2] Definitely, robot receptionists or maids are a huge attraction among visitors because they are something innovative in service, but tourism is a social experience based on service and the most important factor in the tourism business is precisely the people on both sides. Hence the dilemma: **Standardization or Unification?** Discussions about standardization or differentiation have subsided, after arguing that they are not alternative and that standardization is acceptable to the conditions of globalization and differentiation to the conditions of internationalization. Internationalization and globalization are not mutually exclusive processes. They are two basic strategies based on different market presence goals. As for the issues related to innovative approaches in tourism management, they require directing resources to the uncertain and uncertain future, as well as identifying people who are able to think outside the box and innovatively, open to new ideas and concepts. Typically, radical reorganizations and transformations include **"information architecture"**. [3] Proactive managers realize that the digital technologies will continue to redefine the concepts of flexible work, but the capable employee is more important than ever when the **"war for talent"** is already a fact and qualified personnel will dictate the rules in the future. **What is the Role of the Human Capital in Tourism?** This is a question without an unambiguous answer...The main challenges to professionals in tourism are related to the following important question: **How to Manage the Most Valuable Company Asset - Human Capital in Synchrony with Digital Technologies in Order to Become a Source of Competitive Advantage?** (Fig.2) There is no formula for success, but human capital is the only one that can change the competitive environment and in practice successful management requires: *on the one hand*, a willingness to experiment: search for innovative approaches in management and innovative ideas in the application of digital technologies in order to stay ahead of competitors and, *on the other hand*, adaptability to digital changes: adequate deciphering of signals, provided by the external environment and speed adaptation in the direction of competitive management.

HUMAN CAPITAL VS. DIGITALIZATION	
HUMAN CAPITAL	DIGITAL TECHNOLOGIES
On the one hand	On the other hand
Emotional intelligence Creativity Cultural sensitivity Human relationships Personal attitude Human empathy Ability to cope with complex situations Socio-organizational achievements Ability to innovate	Technology sensitivity Traffic Management mobile application systems Marketing Systems Central reservation system (CRS) Customer relationship management (CRM)
THE MAIN PRODUCTIVE FORCE Carries out tourist activities Conducts an active tourist policy Generates competitive advantages	BALANCE BETWEEN AI AND PERSONAL SERVICE RISK: OVER-RELIANCE ON TECHNOLOGY

Fig.2 Human capital vs. Digitalization in Tourism

The Role of Human Capital in Tourism

In the conditions of digital transformations in the tourism industry, the increasing role and importance of human capital and the undeniable relationship between the quality of services and staff productivity are obvious. The tourism business is becoming more and more dependent on the unlimited possibilities of human capital in the process of production and realization of the tourist product, coinciding in time and place, which proves the importance of quality tourist services. The importance of human capital is underlined by the fact that tourism is inherently a service-oriented industry. At the heart of this strategic role of human capital are the three **criteria of the value chain**, which also express the **"HR architecture"** of in the organization. [4] These are: *firstly*, the Human Resource Management (HRM) function: the HRM professionals and their strategic competencies; *secondly*, the Human Resources Development (HRD): the strategically synchronized HRD policy and practices in the organization; *thirdly*, the behavior of people in the organization: strategically focused competencies, motivation and related behavior of people. Managers may rely investments in human capital, rather than in the automation of services, are key to the future success of tourism activities. Therefore, the key role of the Manager is too important. (Fig.3) The next question arises: **How to Unleash the Intellectual Power of Their Staff?** The answer is: emphasis on human capital - the enthusiastic employee changes the competitive environment, productive behavior is a direct result of management the creation of additional value is possible through new characteristics of human capital.

THE KEY ROLE OF THE MANAGER IN TOURISM		
A MEDIATOR OF CHANGE		
ACTIVITY	ROLE	RESULT
Tying the HC to the strategy: (organizational diagnosis)	Management of the strategic HC	Strategy execution
Process reengineering: (shared activities)	Management of company infrastructure	Building an efficient infrastructure
Listening to employees: (providing opportunities)	Individual contribution management	Increase engagement
Transformation management: (providing capacity of change)	Transformation management	Creating a renewed organization

Fig.3. The Key Role of the Manager in Tourism

It is the human factor that unites the material, financial and information resources in the tourist product. People in tourism not only produce the product, but also plan, organize and control the processes taking place with it - they do wonders not only with the rest of the resources, but also with the company, with its competitiveness in the tourist market. Compared to other sectors of the economy, **"invisible human spirit"** [5] in tourism is decisive not only in terms of the main quality characteristics of the tourist product, but also in terms of its competitiveness, which is highly dependent on each member of the tourist staff, on their specific knowledge, skills and organizational behavior. People in tourism not only produce the product, but also plan, organize and control the processes taking place with it - they do wonders not only with the

rest of the resources, but also with the company, with its competitiveness in the tourist market. The creativity and innovation that drives travel marketing, brand development, and guest experience often comes from human professionals who can think outside the box, adapt to new trends, and be empathetic to customer needs. (Fig.4)

MANAGER'S COMPETENCIES "BEYOND TECHNICAL SKILLS"		
BALANCE BETWEEN EMOTIONAL INFLUENCE "CONTAGION" AND RATIONAL INFLUENCE "SUGGESTION"		
SKILLS	QUALITIES	COMPETENCES
Building trust tolerating Differences "pulling" people Gaining authority Delegation of authority Opening to different chapters Creating team spirit Accepting criticism Maintaining composure Reasonable risk taking	Purposefulness Confidence Organization Communicativeness Resourcefulness Determination Tact Devotion Apprehension	Boss Friend Consultant A business partner "Agent" of change Expert

Fig.4. Manager's Competencies "Beyond Technical Skills"

The main challenge facing the tourism industry is the integration of new technologies without compromising on the quality of human interaction. Therefore, talent will drive the digital environment in which we live. New technologies optimizes operational efficiency, but the ability to address guest complaints, understand different cultural expectations, and create a welcoming atmosphere is an inherent human skill.

Interaction of Human Capital and Technologies

The study of the interaction between new technologies and the human factor in tourist activity shows that the successful future of the industry depends on finding the right **balance** between technology and personal service. In the context of digital transformation, tourism is undergoing significant changes that provide new opportunities and challenges. Human capital remains a key element in the success of the industry, with personalized service, emotional intelligence, and the ability to innovate still indispensable. At the same time, digital technologies establishing themselves as a powerful tools that optimizes processes and increases the efficiency of tourist services.

Another logical question: *To What Extent does the Human Capital Management Encompass These Digital Drivers?* There is a difference between what is measured and what is important in essence. These are fundamental questions, as the new economic realities put pressure to expand the focus of activities from the traditional administrative roles performed by him to a broader strategic role in the context of the digitalization of relations between people in the organization and the emergence of new ones between people and "smart machines". Despite the potential of digitalization, the balance between the human factor and new technologies is proving decisive for the sustainable development of tourism. (Fig.5)

INTERACTION BETWEEN HUMAN CAPITAL AND NEW TECHNOLOGIES	
Directions	Aspects
Digital Technology	Introduction of smart technologies Development of smart destinations Creation of digital platforms
Artificial Intelligence	Process automation Service optimization Use of chat bots Predictive analytics
Human Capital	Emotional Intelligence Personalization Communication Skills
Ethical challenges	Danger of reducing employment The need for personal data protection Overcoming technological problems
Balance between HC and new technologies	Trainings for working with new technologies Combining with digital technologies

Fig. 5. Interaction Between Human Capital and New Technologies

Investments in training human capital to work with new technologies, as well as attention to ethical and social aspects, are key to successfully combining the two components. The speedy penetration of digital transformation in tourism has both positive

and negative effects on the sector, digital culture and digital business are among the leading factors for the future development of tourism. The turnover of personnel in tourism is one of the main problems causing the emergence of "**robonomics**" [6] - robots could facilitate the work of people, but not replace them in tourist services. Therefore, the **hybrid workforce model**, where artificial intelligence supports people rather than replaces them, is becoming increasingly popular. In this model, artificial intelligence handles repetitive tasks and processes large amounts of data quickly and efficiently, while human employees focus on high-level decision-making, solving complex problems, and interacting with customers. The effective and prudent use of digital technologies in the field of tourism can significantly improve services, but only if it is in harmony with human capital. This combination will allow the industry to be not only more efficient, but also to preserve its humanity, which is the basis of service quality and competitiveness.

According to the European Union¹ (EU), by 2030, more than 50% of tourism jobs will require digital competencies, which underscores the relevance of the topic. According to data from the World Tourism Organization 2(UNWTO), over 80% of consumers globally use digital platforms to plan and book trips. At the same time, investments in artificial intelligence for customer data management and tourism service optimization are growing by approximately 15% per year. These data underline not only the importance of technology in the sector, but also the need to integrate it effectively. The future of tourism business management will most likely involve a symbiosis between human capital and artificial intelligence. Both sides have their unique strengths, and businesses that successfully combine the two will have a strong competitive advantage. Therefore, one of the priority tasks of tourism management in the context of digital transformation is to find a balance between technology and human capital. [7] In this context, management strategies for integration of human capital and new technologies includes the following components: (Fig.6)

STRATEGIES FOR THE INTEGRATION OF HUMAN CAPITAL AND NEW TECHNOLOGIES	
HUMAN CAPITAL – A DRIVER OF DIGITALIZATION	
1. Adaptability and flexibility in the face of digital transformation	TRAINING PROGRAMS
2. Reorientation towards HC management as a core value	Proper use of the tools of the AI Adding value in areas where AI is not effective
3. Rational use of people's innovative abilities in search of ideas	CLIENT-CENTERED APPROACH
4. Balancing HC and new technologies	Focusing on customer needs
	DEVELOP CREATIVITY AND INNOVATION
	New travel products New adventure experiences New Marketing campaigns
	TECHNOLOGICALLY ACTIVE ROLES
	"Technological adequacy" (to what extent the standards correspond to the technology-based customer service)

Fig.6. Strategies for the Integration of Human Capital and New Technologies

4. Results and discussion

On the basis of the conducted research of World Economic Forum „Future of Jobs Report 2025“ on the role of human capital for innovations in tourism in the conditions of digital transformation, the following generalizations can be made: *on the one hand*, with the quick entry of new technologies and artificial intelligence in tourism, services in the future will be divided into "**high-tech**" and "**high-touch**" and much of the tourists will transform into "**Prosumers**" = ("**producers**" + "**consumers**"), forming a **new type of consumer "intelligent tourist"**. *3On the other hand*, the non-material feature of tourism in the face of human capital is that it brings added value to tourist products and create a special emotional connection with tourists. Continuous training of managers and employees in tourism is an important factor in the reproduction of human capital. The conclusion is that the combination of new technologies and the human capital is not just

¹ https://ec.europa.eu/sectors/tourism/statistics-and-reports_en

² <https://www.unwto.org/>

an opportunity, but a necessity for the modern tourism industry. Only by integrating technology with the values of personalized service can sustainable growth and satisfaction be ensured for both customers and those working in the tourism industry.

5. Conclusion

This study provides information for the the impact of new technologies and artificial intelligence on the tourism industry. In summary, the **general deductions** of the study are reduced to several main ones: **firstly**, digitalization is transforming the tourist industry through the introduction of innovative technologies; **secondly**, human capital remains indispensable in the context of complex and personalized services; **thirdly**, successful tourism management requires training and adaptation of staff to the new realities; **fourthly**, the balance between artificial intelligence and human labor is key to the sustainable development of the sector.

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<https://administracija-i-upravljenje.nbu.bg/en/>

³ <https://www.weforum.org>

The impact of AI on entrepreneurship education

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Abstract: The AI's role in life has increased significantly since the initial introduction of ChatGPT. This trend has drawn the attention of scholars to numerous topics and the entrepreneurship education is one of them. There is already research on the potential of AI in entrepreneurship education and the current paper aims at identifying benefits of AI for entrepreneurship education alongside with potential risks and challenges of its application. The results show that AI can contribute to more personalized education with real environment simulations. Alongside it can improve the assessment. However, challenges like data security, overdependence on AI and AI biases, need to be addressed. The findings identify the need for future examination of specific cases and may contribute to the development of regulations, ethical consideration and development of practices in implementing AI in entrepreneurship education.

KEYWORDS: ENTREPRENEURSHIP EDUCATION, ARTIFICIAL INTELLIGENCE (AI), ACADEMIC ENTREPRENEURSHIP

1. Introduction

The generative artificial intelligence (AI) has become a factor of development for numerous areas of life and the education is certainly one of them. In the current paper we draw attention to two interrelated topics which determine the dynamics of economics. It is inevitably affecting the functioning of market economy by its contribution to promoting the benefits of entrepreneur initiative [1]. Recent years the entrepreneurship education has transformed both its content and methodological approaches. The new realities set by the development of technologies and unpredicted events like the COVID-19 pandemic require the introduction of new methods to teach entrepreneurship both to specialists and nonspecialists [2]. Technological development sets a new framework which allows an improved interaction between teachers and students, more flexibility and engagement in the educational process [3]. AI has the potential to provide a new level and new dimensions in the education on entrepreneurship and its impact on entrepreneurial learning and pedagogical methods needs to be explored.

The research object is entrepreneurship education. **The focus** is the potential of AI to transform entrepreneurship education. **This paper aims** to identify benefits of AI for entrepreneurship education alongside with potential risks and challenges of its application.

The current study is performed in the context in a scientific project "Academic Entrepreneurship Roadmap", funded by Erasmus+ Programme, Action type KA220-HED - Cooperation partnerships in higher education, 2023. It aims to thoroughly examine the benefits of entrepreneurship education from a variety of angles, with a focus on students, faculty, and business professionals. The latter context determines that the current examination of the AI's role in entrepreneurship education uses a limited range of **research methods**, namely desk research and review of current studies on the topic. **The authors' standpoint** is that the AI provides more tools for entrepreneurship education but also leads to various challenges and risk.

The paper structure follows the main purpose and aims of the research, i.e., after the introduction, the second part presents a literature review based on current research in the field of AI in entrepreneurship education. The third section focuses on the research methodology. The latter serves as the study's framework and as the foundation for the fourth section, which presents the empirical findings. The paper concludes with conclusions and recommendations for future research on the implementation of AI in entrepreneurship education and its consequences.

2. Literature Review

2.1. AI Transformation in Education

AI has been transforming the education in numerous ways. The latter include automating instructional tasks, analyzing learning data, and implementation of more personalized teaching approaches [4]. In this regard some researchers conclude that the implementation of AI can make learning more student-centered and

equitable [4]. Thus, in general AI contributes to more personalized and adaptive learning, but also helps in assessments of the students.

Opportunities for More Personalized and Adaptive Learning

AI provides experience that meets the individual student needs. Through machine learning algorithms and data analytics, AI systems analyze learners' strengths, weaknesses, and preferences and has the potential to adapt everything – the instructions, the content, etc. [5]. For example, such platforms can modify task difficulty in real time to keep students challenged without demotivating them [6]. Such approach allows students to set learning goals, enhances competence through personalized challenges, and strengthens the connection with the students by using such AI tools [7]. There are studies, which show such systems have the potential to improve academic performance compared to traditional methods, which is empirically tested [5].

Furthermore, AI makes the learners more engaged through real-time feedback mechanisms. For example, voice and facial recognition technologies check student participation and even their emotional states during lessons. Thus, the educators can adjust their teaching strategies at the same moment [8]. If a student appears disengaged, the system might propose to introduce more interactive content to awake interest. Such adaptational approaches are related to neuroscience and educational psychology. They aim to ensure that the methods are in line with needs of the student and the acquisition of knowledge. Thus, it ensures that the interaction between learners and teachers is effective [9].

AI Application in Assessments Process

The application of AI for assessment can rely on several tools. They can automate grading and provide feedback to students. This can be performed by using machine learning models to grade essays or generate adaptive quizzes. The latter can reduce tutors' workload and improve the consistency of assessment.

Such approach for assessments is transforming the education by providing a lot of benefits and innovative applications. One of them is the ability to make the learning experiences more personalized by adaptive testing. Such approach is based on developing question with a difficulty and content, adapted to the individual student needs. The studies show that it improves the engagement and performance of students. [10]

Furthermore, automated systems (including AI) assist in evaluation of assignments and essays, where they can be useful in ensuring more consistency and accuracy. Thus, the human biases in grading can be reduced [11]. Thus, the automation reduces the time spend and focus more on making the education process more effective. The real-time feedback is another benefit of the AI introduction in assessment process. AI can provide immediate feedback on the students' performance and receive more focused instructions for further improvements. [10] Alongside, the educators are able to provide more targeted advice for student's future work [12].

The application of AI in the assessment process provides a more personalized, efficient, and effective learning. The latter leads to higher level of material acquisition and the ability to practical application of the acquired knowledge [13].

2.2. The Benefits of AI for Entrepreneurship Education

The standard approaches in entrepreneurship education have emphasized on experiential learning through creation of business plans, competitions and case studies. The introduction of information and communication technologies (ICTs) creates new teaching-learning models. Furthermore, AI represents a brand-new level by providing the opportunity to create an adaptive curriculum that corresponds to the individual needs of the learner. Chen et al. (2021) identify three evolutionary phases in teaching entrepreneurship - passive knowledge transfer (pre-2010), interactive digital tools (2010–2020), and AI personalization (post-2020).[14]

The AI has also an innovative effect on the entrepreneurship education. It fosters creative problem solving and thus develops the innovative thinking and creativity. Furthermore, it creates environment for experiential learning and more intensive collaboration among students. From the point of view of skills acquisition AI helps in the identification of various market trends and consumer preferences, assisting students in their business ideas [15]. It also provides support for future entrepreneurs to test their decision-making skills in a risk-free simulation [16]. Furthermore, AI contributes to creation of knowledge-sharing environment and collective creativity, which involves many perspectives and improves the innovation in its earliest stage [17]. However, such introduction of AI requires development of AI literacy of tutors and alongside following any ethical considerations and their latest changes [15] [16].

2.3. Potential of Specific AI Tools for Entrepreneurship Education

Generative AI

Generative AI tools, such as ChatGPT, can be utilized in various ways. On one hand they are very useful in generation of ideas and creating an interactive learning environment. Furthermore, the students can test their business concepts, simulating customer interactions, and even refine pitches through generation feedback on it. At first glance this may sound like the students do not need to be creative and think anymore, but studies show that generative AI improves their ability to critically evaluate business ideas. AI becomes a kind of tutor for them and stimulates their creativity, bridging theoretical knowledge with its practical application [18] [19].

Machine Learning & Big Data

Machine learning and big data learning support future entrepreneurs in proving them with advanced knowledge and skills to identify market trends, assess opportunities, and optimize strategies. They can identify consumer preferences and potential gaps supporting their decision making [20] alongside allowing them to allocate resources efficiently and mitigate risks [21].

Chatbots and Virtual Assistants

Such tools assist the students in understanding better the business planning by automating competitor analysis, financial modeling, and customer persona development. They can provide them with access to industry benchmarks and regulatory requirements. Thus, they reduce research time while improving accuracy. [22]

Business Simulations and Gamification

Platforms with AI, which create gamified business environments, provide the future entrepreneurs with an environment in which very realistic scenarios for virtual companies are created. In these platforms may be incorporated various challenges like

supply chain disruptions, business negotiations, problem-solving, etc. There are also gamification perspectives, which are about tracking of the progress, rewards, etc. They are proven to increase interest, engagement and dedication. [23]

Pedagogical Support

There are AI systems which main purpose is to be a kind of pedagogical partners (for example Edthena). They can provide feedback on a proposed business plan and teaching methodologies. They can analyze the submissions of students as well. Furthermore, these tools can identify gaps and even recommend resources, supporting the learning process [24].

2.4. Risks and Challenges before the Application of AI in Entrepreneurship Education

Although AI has great potential in improving entrepreneurship education, several challenges must be taken into consideration. The integration of artificial intelligence (AI) in entrepreneurship education presents significant opportunities but also comes with substantial risks and challenges.

The most common concern about the introduction of AI is the potential loss of the analytical skills of humans to make decisions. This risk comes from AI-driven tools making predictive analysis and business simulations. This may lead to high level of reliance on technology compromising their critical thinking and problem-solving abilities [25]. It also reduces the role of person of entrepreneur by limiting the nuances of decision making related to the very specifics of the situations and entrepreneurs' intuition [26].

Alongside, there are issues related to the algorithms. AIs are "educated" based on historical data, but it can contain biases, which of course will affect the recommendations and learning outcomes [27]. Such risks present a high threat to the decision making of the future entrepreneurs if they fully rely on AI for market opportunities, funding decisions, or prediction of customer behavior.

Data privacy is another challenge in the use of AI in entrepreneurship education. The AIs require a lot of personal data to be able to give back personalized answers. These issues are related to the data protection regulations [28]. Thus, universities and educators must take into consideration the data policies to safeguard student information while using AI.

Last, but not the least any institutional resistance to AI application is challenge to education. Some of the educators lack the expertise to use AI as one of their teaching tools [26]. This requires expertise development to improve AI literacy among tutors, ensuring that the AI will add to the educational approach and not substitute it.

3. Methodology of the Research

The current study uses desk research based on a literature review of the studies focused on the implementation of AI in entrepreneurship education.

At the first stage we made a list of various studies on the topics. This includes most recent works (from last five years) alongside older works, which are relevant to the current state-of-art. Next, we reviewed the statements and conclusion to identify similarities in the benefits of AI, but we also searched for challenges and risks in its implementation. Finally, we summarized the information under topics and subtopics, represented in the structure of the paper.

It should be underlined that the current work does not cover all the studies in the examined area and thus does not state that these are all benefits and risks in AI application in entrepreneurship education.

4. Discussion and Results

AI's role in entrepreneurial competency development is inevitable. It contributes to critical thinking, creativity, and business planning [29] [30]. It can be applied to enhance teaching strategies and learning outcomes by using AI-driven tutoring and student engagement [31] [32]. It has been proven that the use of deep learning improves student motivation and psychological readiness [33].

Alongside there are some challenges and Ethical considerations, which need to be taken into consideration. It may increase dependence on AI and lead to underestimation of human intuition in entrepreneurship. More efforts are necessary in insuring data privacy, bias in AI models, and ethical dilemmas [34].

These have led us to the understanding that AI should not be solely utilized but there is a need for AI-human collaboration in entrepreneurship education [35].

3. Conclusion

The integration of AI in entrepreneurship education represents a significant transformation in how future entrepreneurs are educated, trained and assessed. The current paper synthesized some research on the utilization of AI's and its role in educational strategies, curriculum development and the assessment. The findings show that AI tools such generative AI, machine learning, etc. contribute to easier opportunity recognition, simulation of real business environment and personalization of the learning process. However, there are serious concerns such as ethical dilemmas, algorithmic biases, and the risk of over-reliance on automated systems, which require certain measures.

The study provides a framework on benefits and challenges but further investigation on various aspects is required to ensure a human-centric approach to technological integration in entrepreneurial training. Future research should focus on case studies, AI's long-term impact on entrepreneurial success (as far as there is data) and the emerging trends in AI-driven business incubators and accelerator programs.

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A comparison of Computer Forensic Tools

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Abstract: This paper discusses key challenges and methods in computer forensics and presents a comparative analysis of forensic software tools FTK, Autopsy, The Sleuth Kit TSK, TestDisk and Foremost. The instruments considered in the study are applied in different case studies to collect, analyze and preserve digital evidence available for computer forensics, cybersecurity and cloud-based investigations. The research discusses their effectiveness and limitations in handling cloud-based evidence collection.

Keywords: COMPUTER FORENSIC TOOLS, COMPUTER FORENSICS

1. Introduction

With the rapid adoption of cloud computing, digital forensic investigations have become increasingly complex. This study evaluates the effectiveness of five widely used forensic tools—Forensic Toolkit (FTK), Autopsy, The Sleuth Kit (TSK), TestDisk, and Foremost focusing on their capabilities in cloud-based investigations and evidence collection. The author of the paper explores the integration of Python-based automation to enhance forensic processes. The case studies analyze the applicability of these tools in real-world forensic scenarios involving cloud environments.

Cloud computing offers significant advantages, such as scalability, remote accessibility, and cost efficiency. However, these benefits introduce challenges for digital forensics, including jurisdictional issues, data volatility, and third-party control over evidence. The objective of this study is to assess the effectiveness of forensic tools in acquiring, analyzing, and preserving digital evidence from cloud-based environments, with a focus on Python scripting for automation. The study presents a comparative analysis of five forensic tools by examining their applications in real-world cloud forensic cases [1,2].

2. Digital forensic investigations in cloud environments

Digital forensic investigations in cloud environments require specialized tools that are widely used forensic software possessed characteristics such as remote data acquisition, cloud storage analysis, reporting on cloud-based evidence, and forensic imaging.

The forensic instruments acquire and examine data from cloud services like Amazon Web Services (AWS), Azure, OneDrive, Google Drive, and Dropbox and also extracts metadata from cloud snapshots and logs. They support forensic analysis of AWS Elastic Block Store (EBS) snapshots, Azure virtual hard disks, and Google Cloud Persistent Disks and collect live RAM, volatile data from running cloud instances, logs from cloud instances. The deleted files, logs, and databases from cloud-based virtual disks are recovered and suspicious actions such as unauthorized file access or privilege escalation are identified. Logs from AWS CloudTrail, Azure Monitor, and Google Cloud Logging are extracted and after analyzing the instruments identify user activities, access patterns, and unauthorized modifications. The forensic tools provide comprehensive indexing, filtering, and keyword searching for structured cloud data. They support remote forensic imaging of virtual machines and cloud storage. Cryptographic hashing (MD5, SHA-1, SHA-256) to verify file integrity is used in cloud storage. The digital instruments use application programming interfaces to extract data from cloud platforms while maintaining forensic integrity for Artificial Intelligent-driven analytics for detecting anomalies in cloud environments. Cloud forensics poses several challenges that differentiate it from traditional forensic investigations. Unlike conventional computer forensics, where investigators have physical access to storage devices, cloud forensics relies on remote access to virtualized environments. Cloud service providers host multiple clients on shared infrastructure, making it difficult to isolate and extract specific forensic data

without violating privacy regulations. Cloud data is frequently updated, overwritten, or deleted, making it challenging to acquire consistent forensic evidence. Data in cloud environments can be stored in multiple geographic locations, leading to legal complexities related to data ownership, access rights, and compliance with different regulations. Cloud providers may not offer full access to system logs, limiting forensic investigators' ability to trace malicious activities [3,4,5].

The study explores various case studies that illustrate Python's impact on the forensic analysis, and how to improve the efficiency and effectiveness of forensic investigations.

3. Case studies

Case study 1: Cloud-based data acquisition with FTK and Python

Scenario: A corporation detects unauthorized access to its cloud-based database on Amazon Web Services (AWS). The security team needs to extract and analyze logs to determine the breach's origin and impact.

Application of FTK and Python (Fig.1): FTK is used to acquire AWS CloudTrail logs and extract metadata. Python scripts automate log parsing and keyword searches. Decryption scripts in Python assist in analyzing encrypted files. The timeline analysis feature reconstructs the attack sequence.

```
import json

def parse_cloudtrail_logs(log_file):
    with open(log_file, 'r') as file:
        logs = json.load(file)
        for event in logs['Records']:
            print(f"Event Time: {event['eventTime']}, User: {event['userIdentity']['arn']}, Action: {event['eventName']}")

parse_cloudtrail_logs('cloudtrail_logs.json')
```

Fig. 1 Python Script for Log Parsing.

Findings: Suspicious login attempts are traced to a compromised employee account. Data exfiltration logs are retrieved, confirming unauthorized file transfers. The evidence is compiled into an admissible forensic report.

Case study 2: Open-source cloud log analysis with Autopsy and Python

Scenario: An institution suspects internal fraud involving unauthorized file access within its Google Drive environment.

Application of Autopsy and Python (Fig. 2): Autopsy parses Google Drive activity logs. Python scripts automate metadata extraction and timestamp analysis. Keyword searches identify fraudulent transactions.

```
import pandas as pd

def extract_metadata(log_file):
    df = pd.read_csv(log_file)
    suspicious_activity = df[df['Action'] == 'Download']
    print(suspicious_activity[['User', 'Timestamp', 'File']])

extract_metadata('google_drive_logs.csv')
```

Fig. 2 Python Script for Metadata Extraction.

Findings: Unauthorized file downloads are detected outside business hours. Deleted files are partially recovered using Autopsy's data recovery features. Metadata analysis is linked an employee to unauthorized actions.

Case Study 3: Cloud virtual disk analysis using the Sleuth Kit (TSK) and Python

Scenario: An agency receives an order to analyze a suspect's cloud-hosted virtual machine (VM) stored on Microsoft Azure.

Application of TSK and Python (Fig. 3): TSK extracts files and metadata from the virtual disk. Python scripts automate hash analysis for file integrity verification.

```
import pandas as pd
import hashlib

def verify_hash(file_path, expected_hash):
    with open(file_path, 'rb') as file:
        file_hash = hashlib.sha256(file.read()).hexdigest()
        return file_hash == expected_hash

print(verify_hash('suspect_file.img', 'expectedhashvalue'))
```

Fig. 3 Python Script for Hash Verification.

Findings: Deleted chat logs from an encrypted messaging app are recovered. Forensic timeline analysis reveals suspicious activity before a wipe attempt. Recovered evidence is used in criminal proceedings.

Case Study 4: Cloud-based partition recovery with TestDisk and Python

Scenario: A cloud service provider experiences a ransomware attack that corrupts a customer's virtual server partitions, making critical business files inaccessible.

Application of TestDisk and Python (Fig. 4): TestDisk identifies and repairs damaged partitions. Python scripts automate file recovery verification.

```
import pandas as pd
import os

def check_recovered_files(directory):
    recovered_files = os.listdir(directory)
    print("Recovered Files:", recovered_files)

check_recovered_files('/recovered_data/')
```

Fig. 4 Python Script for File Recovery Check.

Findings: Partition structure is restored, and business-critical files are recovered. Attack vector is identified, helping prevent future incidents.

Case Study 5: Cloud file recovery and carving with Foremost and Python

Scenario: A cybersecurity team investigates a data breach involving unauthorized deletion of sensitive files from a company's Dropbox cloud storage.

Application of Foremost and Python (Fig. 5): Foremost carves lost files from a forensic image. Python automates file classification and validation.

```
import os

def classify_files(directory):
    file_types = {".pdf": "Documents", ".jpg": "Images", ".txt": "Text Files"}
    for file in os.listdir(directory):
        ext = os.path.splitext(file)[1]
        print(f"{file}: {file_types.get(ext, 'Unknown')}")

classify_files('/recovered_files/')
```

Fig. 5 Python Script for File Classification.

Findings: Deleted files containing intellectual property are restored and a compromised employee account is identified.

Case Study 6: Full forensic workflow automation using TSK and Autopsy (Fig.6 and Fig. 7)

```
import pytsk3
import os
import subprocess
from autopsy.lib import Autopsy

# Define the path to the disk image
image_path = 'disk_image.dd'

# Open the disk image using PyTSK
img = pytsk3.Img_Info(image_path)
fs = pytsk3.FS_Info(img)

# Function to extract file metadata and recover deleted files
def extract_files_and_recover(fs):
    recovered_files = []
    for root_dir in fs.open_dir("/"):
        for entry in root_dir:
            if entry.info.name:
                file_name = entry.info.name.name
                file_path = os.path.join("/", file_name)
                try:
                    if entry.info.meta and not entry.info.meta.deleted:
                        # Collect metadata and recover the file
                        print(f"File: {file_path}, Size: {entry.info.meta.size} bytes")
                    elif entry.info.meta and entry.info.meta.deleted:
                        # Recover deleted files
                        print(f"Recovered Deleted File: {file_path}")
                        recovered_files.append(file_path)
                except:
                    pass
    return recovered_files

# Function to analyze timestamps and create a report
def analyze_timestamps(files):
    timestamps_report = {}
    for file in files:
        metadata = get_file_metadata(file) # Custom function to get metadata
        timestamps_report[file] = metadata['timestamps']
    return timestamps_report

# Generate a report in Autopsy
def generate_report(files, timestamps_report):
    report = 'Forensic Investigation Report\n'
    report += '=====\n'
    for file in files:
        report += f"File: {file}, Timestamp: {timestamps_report[file]}\n"
    # Save report to a file
    with open('forensic_report.txt', 'w') as report_file:
        report_file.write(report)
    print("Report generated!")

# Full Workflow Automation
def run_forensic_workflow():
    recovered_files = extract_files_and_recover(fs)
    timestamps_report = analyze_timestamps(recovered_files)
    generate_report(recovered_files, timestamps_report)

# Execute the forensic workflow automation
run_forensic_workflow()
```

Fig. 6 Forensic Workflow Automation.

```
# Generate a report in Autopsy
def generate_report(files, timestamps_report):
    report = 'Forensic Investigation Report\n'
    report += '=====\n'
    for file in files:
        report += f"File: {file}, Timestamp: {timestamps_report[file]}\n"
    # Save report to a file
    with open('forensic_report.txt', 'w') as report_file:
        report_file.write(report)
    print("Report generated!")

# Full Workflow Automation
def run_forensic_workflow():
    recovered_files = extract_files_and_recover(fs)
    timestamps_report = analyze_timestamps(recovered_files)
    generate_report(recovered_files, timestamps_report)

# Execute the forensic workflow automation
run_forensic_workflow()
```

Fig. 7 Forensic Workflow Automation Report.

Scenario:

A suspect's digital device is investigated and a full forensic analysis of a disk image is conducted. This includes extracting files, analyzing timestamps, recovering deleted files, and creating a detailed report. Automating these processes will save time and reduce human error.

Solution:

A Python script is created to automate the entire forensic investigation workflow. The script integrates TSK for disk image analysis and Autopsy for generating visual reports and identifying key evidence. The script automates the process of recovering files from a disk image, extracting metadata, and identifying deleted files. It analyzes file timestamps and generates a forensic report that lists all recovered files and their metadata. The final report is saved as a text file, which can be used for presentation in court or further investigation. The entire forensic workflow from file extraction to report generation is automated, saving valuable time for the forensic investigator. The script integrates with TSK for deep disk analysis and recovery and can be extended to work with Autopsy for visualization and case management [6,7,8,9].

4. Results and Discussion

Cloud-Based Data Acquisition

FTK successfully acquired structured log data from AWS, Google Drive, and Azure, identified metadata changes in cloud storage, which assisted in tracking unauthorized file modifications.

Autopsy parses metadata from Google Drive logs but struggled with real-time data acquisition from cloud platforms. It requires additional plugins for improved compatibility. TSK extracted raw forensic images of cloud-hosted virtual machines but required manual processing to interpret filesystem structures. TestDisk has limited functionality in direct cloud acquisition but proved effective in recovering lost partitions in virtualized environments. Foremost is not suitable for direct cloud data acquisition but performed well in carving deleted files from forensic disk images of cloud storage.

Log Analysis and Metadata Extraction

FTK parsed CloudTrail and Google Drive logs, highlighting unusual access patterns. FTK flanges unauthorized logins using timeline analysis. Autopsy provides keyword-based search and metadata analysis but lacked advanced timeline correlation. TSK allows forensic-level examination of log files, including hexadecimal-level review of file system metadata. Custom Python scripts automates anomaly detection, identifying suspicious login attempts and file access outside working hours.

Virtual Disk and Partition Recovery

TSK successfully extracts files and metadata from Azure and AWS virtual disk snapshots and detects hidden partitions used for storing unauthorized files. FTK identifies and reconstructs partially corrupted virtual disk segments, recovering deleted chat logs. TestDisk restores partitions affected by a ransomware attack, allowing business-critical files to be recovered with minimal data loss.

File Carving and Deleted Data Recovery

Foremost recovers deleted intellectual property files from forensic images of Dropbox cloud storage. Autopsy identifies deleted document fragments and reconstructs them using keyword analysis. Python automation assists in filtering false positives in file carving results, improving efficiency in data validation.

Comparative Analysis (Table 1)

Each forensic tool exhibits strengths and weaknesses when applied to cloud-based investigations. FTK, as a commercial tool, offers robust data acquisition capabilities and advanced search functions, making it highly effective for structured forensic investigations. Autopsy, an open-source alternative, provides a user-friendly interface and built-in analysis features but requires additional configurations for cloud environments. The Sleuth Kit (TSK) excels in raw data extraction and forensic analysis but demands higher technical expertise. TestDisk is primarily designed for partition recovery, making it valuable in scenarios where cloud-based disk corruption or ransomware attacks occur. Foremost, a file carving tool, is useful for reconstructing deleted files but lacks native integration with cloud storage platforms.

Table 1: Comparative Findings.

	FTK	Autopsy	TSK	TestDisk	Foremost
Cloud Data Acquisition	++	++	+	+	+
Log Analysis	++	++	++	+	+
Virtual Disk Analysis	++	++	++	++	+
Partition Recovery	+	+	++	++	+
File Carving	++	++	+	+	++
Python Integration	Limited	Good	Excellent	Moderate	Good

The programming language Python enhances forensic workflows by automating repetitive tasks such as log parsing, metadata extraction, and integrity verification. While TSK benefits significantly from Python scripting, FTK's proprietary nature limits

its automation potential. Autopsy and Foremost integrate well with Python for enhanced forensic efficiency.

5. Conclusion

Cloud-based forensic investigations require tools capable of acquiring, analyzing, and recovering evidence from distributed environments. While commercial tools like FTK offer comprehensive forensic capabilities, open-source alternatives such as Autopsy, TSK, TestDisk, and Foremost provide flexible and cost-effective solutions. Python automation enhances forensic workflows, improving efficiency in data parsing, hash verification, and log analysis. Future research should explore further integration of AI-driven forensic techniques to enhance cloud evidence collection and analysis.

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A mobile application for Android supporting self-study in technical sciences

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Abstract: Nowadays advancing world of technology, mobile applications are rapidly growing segment of global mobile market. The proposed application aims to support self-learning of students, but also to facilitate the learning process, by offering a teaching panel where courses can be created and lectures can be added to them. The application was designed using the Android Studio programming environment and was written in the Java programming language. It is fully dynamic, as all information entered by the user being stored in a database.

Keywords: EDUCATION, MOBILE DEVICE, PROGRAMMING, JAVA

1. Introduction

Mobile technologies are entering many aspects of our daily lives with incredible speed, increasing our independence in terms of time and space.

According to the glossary of e-learning terms [3], the meaning of e-learning is as following: Education via internet, network or computer. This means that e-learning refers not only to the free (or sometimes paid) information resources available on the Internet, these are the other aspects of online learning, which if not private is assumed, that it should be of the type of free and accessible online education.

The main goal of the paper is to present a designed and created mobile application to support the self-learning and the self-training of students in technical sciences, through which knowledge and skills can be acquired in a convenient and easy way for students. The program was developed for computer science education at the National Military University.

In [4], a comprehensive concept for database management is proposed, which includes the different stages of their creation, as well as the specifics that each must comply with. The inclusion of emotions in a learning process is essential, as it affects not only the rational, but also the emotional level, and the acquired knowledge is more lasting. Continuing the overall view of the cognitive elements of a learning project, [5] presents the creation of a mind map and an algorithm for project, which is extremely useful in the design and development of a project supported by an appropriate application as a final product.

2. Mobile application.

Teachers, students and learning materials can be located in different places and interact at different times. In [1], different categories of e-learning are presented according to the time and location of the participants in the learning process. The main aspects (see fig. 1) to be considered when choosing an e-learning form and its implementation are:

- psychological – how does a given electronic tool affect the motivation for learning, the attitude towards the subject;
- pedagogical – how well the chosen form corresponds to the general organization of the course;
- methodological – does the chosen resource and format help to better absorb the material;
- organizational – rational structuring of the learning content.



Fig. 1 Aspects influencing the choice of an educational electronic form

Description of the mobile application's operation

Android is an operating system based on Linux for mobile devices. Android platform provides a rich application framework that allows developers to build innovative apps in the Java language environment. The proposed application aims to support self-learning of students, but also to facilitate the learning process, by offering a teaching panel where courses can be created and lectures can be added to them. The application was designed using the Android Studio programming environment and was written in the Java programming language. It is fully dynamic, as all information entered by the user being stored in a database (Firebase firestore). The application contains a login and registration page, and a Firebase Authentication product is used to create and log in to an account. The application contains three sections: a home page, a page with all courses, and a page containing all courses for which a user has enrolled (student panel) or with all courses created by a teacher (teacher panel). Teaching panel contains a button to create a course and a button to create lectures.

Mobile application design and functionality

Using the guidelines of [2], [6], [13] and [16], to create the applications, the general form of a mobile application for Android, supporting self-learning in technical sciences, is presented in figura 2. In [7] the possibilities of military education in the training of cadets in the National Military University in Bulgaria are presented, which is a good opportunity to draw experience and tailor the application to the specific needs that these trainees have. In [11] and [12] describe the need for data protection, which is an important issue that must be addressed when creating any mobile application.

The design of the application aims to provide clear and seamless navigation when using the application and to make working with it as easy as possible, using a number of components from the Android Studio component menu, which are visible in figure 2.

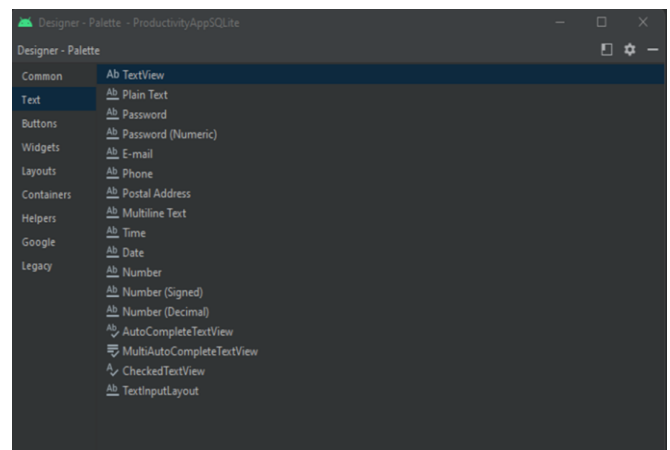


Fig. 2. Designer-Pallet of Android Studio

Upon initial access to the application, a login page (*LoginActivity*) opens (see Fig. 3), where the main components are:

- *TextView*;
- *EditText*;
- *Button*.

Through them, the user can enter the necessary data and log in to their account. If the user has not created an account, by clicking on the *TextView* (*No Account, Registracion*) button to create an account, which is presented in figura 3, all will be redirected to the registration page (*RegisterActivity*), which can be seen in figure 4.

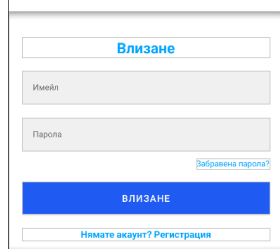


Fig. 3. *Layout_login.xml*

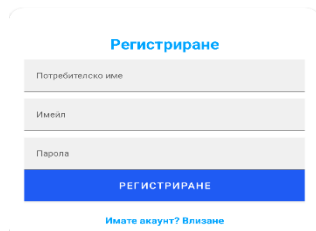


Fig. 4.. *Activity_register.xml*

Depending on whether the user's profile is a teacher or a student, the application view will have a different appearance. A teacher profile will be created manually, directly in the database.

Selecting the "Courses" button opens a page containing a list of all existing courses, which is presented in figure 5. In addition to a list of all courses, there is also a button component (*FloatingActionButton*). When this button is selected, an *AlertDialog* component opens (see Fig. 6), which allows the selection of the necessary components for creating a new course. The newly created course is added to the list of all courses.

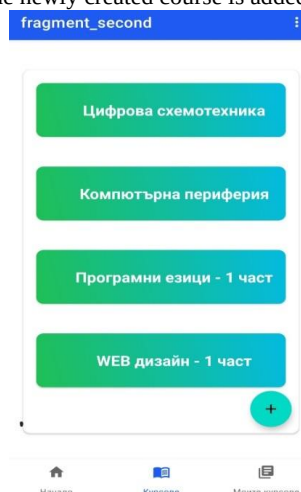


Fig. 5. *SecondFragment.class*

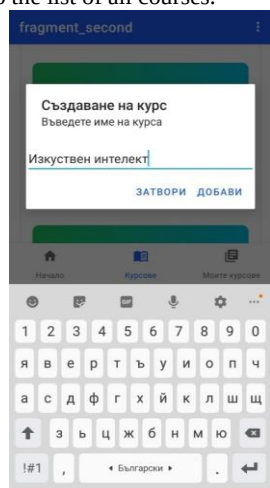


Fig. 6. *AlertDialog – creating a course*

In order to add a lecture, the teacher must select a button (*FloatingActionButton*), that allows to open a component page, where to enter information to create a lecture and implement the addition using *AddLessonsActivity.class*, the corresponding visualization is proposed in figure 7. The information that each teacher must enter is:

- Name of the lecture;

- Attached a file containing the entire lecture, from the mobile device repository.

Attaching a file is accomplished by the user clicking the component *EditText* → "Select a file from storage", after which it will be redirected to the internal storage of mobile device, from where the desired file in .doc, .pdf format is selected.

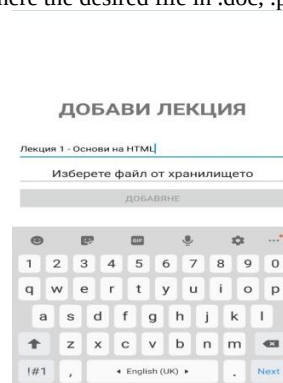


Fig. 7. *AddLessonsActivity.clcs*

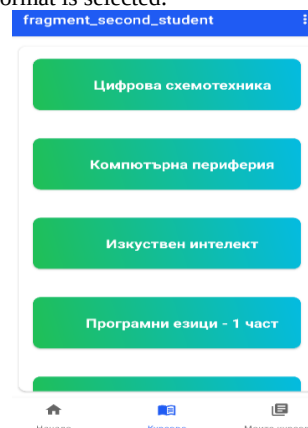


Fig. 8. *Final appearance of the application.*

The current and final form of an Android mobile application supporting self-study in technical sciences is presented in figure 8. The Firebase Authentication tool is used to create and manage user accounts, as well as to access the mobile application. [8], [9], [10].

The design of the mobile application is designed in the form of XML code, and the written code will be stored as an XML file

In [14] and [15] another aspect of education in Republic Bulgaria is presented.

3. Conclusion

The implementation of mobile technologies has not bypassed the field of education. These technologies enrich the desktop-based learning environment with a mobile communication channel, and most importantly, they are a huge step in overcoming the dependence of education on time, space, and other factors.

The main advantages of the created mobile applications are:

- easy portability between different platforms;
- the ability to control user rights at the virtual machine level;
- and, most importantly, a high level of security.

These advantages compensate for the main disadvantage of mobile apps, namely the need for additional resources.

The current mobile app offers another insight and self-learning opportunity to anyone, at a convenient time, place and setting. It allows for multiple iterations and is a prerequisite for reinforcing and enhancing knowledge, in a relaxed and comfortable environment for the student. The application is still under development and its functionalities are being enriched.

4. Acknowledgement

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A Review of the Modern Software Systems and Tools in Logistics for Digital and Smart Manufacturing

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Abstract: Logistics represents an industrial and multidisciplinary scientific field that deals with the analysis, planning, management, and control of all logistics operations (distribution, warehouse, shipping, transportation etc.). Modern trends in logistics involve the use of advanced software systems, tools and digital technologies (DT) to address all operations and activities within a single logistics task. Digital technologies (DT) in logistics encompass the application of intelligent and smart digital technologies, smart technologies (ST), smart manufacturing (SM), smart logistics (SL), artificial intelligence (AI), cloud computing (CC), data mining (DM), and more. The application of all these technologies in logistics has created a new concept called Logistics 4.0, which is based on the concept of Industry 4.0. While SMEs (small and medium-sized enterprises) and corporations in middle-developed and underdeveloped countries of the world are beginning to think about introducing the concept of Logistics 4.0, a new concept of Logistics 5.0 has already been created and defined. Within the Logistics 4.0 concept, which is part of Industry 4.0, advanced and modern versions of software systems and tools in the field of logistics are used for planning, transportation, warehousing, distribution and other logistics operations. Modern software systems and tools for logistics are classified into several groups: logistics database (LDB) for quick search and access of logistics data, logistics information systems (LIS) for storing, processing and management of logistics data and information, logistics management systems (LMS) for managing logical operations, logistics decision support systems (LDSS) for decision-making in specific logistics operations, logistics expert systems (LES) and other software systems and tools for logistics operations. This paper provides an overview of different software systems and tools for logistics operations.

KEY WORDS: LOGISTICS, LOGISTICS 4.0, SOFTWARE SYSTEMS AND TOOLS, LOGISTICS DATABASE (LDB), LOGISTICS INFORMATION SYSTEMS (LIS), LOGISTICS MANAGEMENT SYSTEMS (LMS), LOGISTICS DECISION SUPPORT SYSTEMS (LDSS), LOGISTICS EXPERT SYSTEMS (LES).

1. Introduction

Logistics is an industrial and multidisciplinary field that focuses on the management of goods, services, and related products from the point of origin to the point of consumption, with the aim of meeting customer requirements. It includes operations such as analysis, planning, purchasing, management information, distribution, shipping, transportation, quality control, warehousing, and more, ensuring the efficient and effective movement and storage of goods and services [9,10,14,17,25-27,37,53,69]. The foundational definition of logistics was established by the Council of Logistics Management (CLM) in 1991.

The logistics of physical items typically involves the integration of information flow, material handling, manufacturing, packaging, shipping, inventory, transportation, distribution, warehousing, often and security, and more.

Logistics is closely linked to the supply chain (SC), and in modern business practices, these two areas are often integrated. Furthermore, logistics management (LM) is increasingly aligned with supply chain management (SCM). This integration has led to the development of a new concept known as supply chain logistics (SCL) [17,18,31,49].

In large companies, all logistics activities are centralized within a dedicated logistics department. In contrast, small and medium-sized enterprises (SMEs) and similar organizations often distribute logistics functions across various departments. Additionally, some companies outsource specific logistics services to specialized providers, either partially or fully. These companies, which manage and execute such outsourced logistics operations, are known as logistics service providers (LSPs).

The ultimate domain of logistics is the development and application of Logistics 4.0, which is used in the new

concepts of digital manufacturing (DM), smart manufacturing (SM), Industry 4.0, etc.

Within the concept of Logistics 4.0, modern logistics models are used, such as: digital logistics (DL), distribution logistics (DL), green logistics (GL), reverse logistics (RL), smart city logistics (SCL), supply chain logistics (SCL), smart logistics (SL), sustainable logistics (SL), smart urban logistics (SUL), sustainable urban logistics (SUL), urban logistics (UL) etc. The main trend in the development of new types of logistics is the inclusion of smart technologies in logistics [17,23,35,42,59].

The size of the global logistics market is valued at 10.2 trillion \$ in 2023. Consulting firm AMR (Allied Market Research) predicts that it will reach 20.1 trillion \$ by 2033, with a CAGR (compound annual growth rate) growth of 7.3% from 2034 to 2034.

For the field of logistics, the Scopus of citation database has indexed 843.942 publications in the "Article title, Abstract, Keywords" option and 54.535 publications in the "Article title" option (as of 31-12-2024).

The aim of this paper is to describe the different variants of software systems and tools for logistics, as well as the possibilities of their application in all areas of human activity.

2. From Logistics 1.0 to Logistics 4.0

Analogous to the historical development of industry from Industry 1.0 to Industry 4.0, many authors have begun to present a similar evolution of logistics from Logistics 1.0 to Logistics 4.0 (Fig. 1) [17,19].

Logistics 4.0 is a new generation of logistics and logistics management (LM), which is based on a combination of modern software systems, tools and digital technologies (DT). It ensures integral and intelligent cooperation for the

implementation of logistics operations, which the physical, digital and virtual worlds are connected.

Some of the most significant digital technologies (DT) applied in Logistics 4.0 include [17,19,21,32,33,44,64]: Internet of Things (IoT), Internet of Everything (IoE), Internet of People (IoP), Internet of Services (IoS), robotics, sensors, artificial intelligence (AI), cloud computing (CC), logistics-as-a-service (LaaS), cyber-physical systems (CPS), smart manufacturing (SM), augmented reality (AR), blockchain, data mining (DM),

networks (4G, 5G, 6G, WAN, WBAN, WSN, WiFi etc.) etc.

Along with the development of Logistics 4.0, the development and application of new concepts of digital production (DM), smart production (SM) and Industry 4.0, have predicted the development of accompanying areas with a similar admixture of "4.0", such as: Marine 4.0, Maritime 4.0, Port 4.0, Quality 4.0, SC4.0 (supply chain 4.0), Transport 4.0, etc.

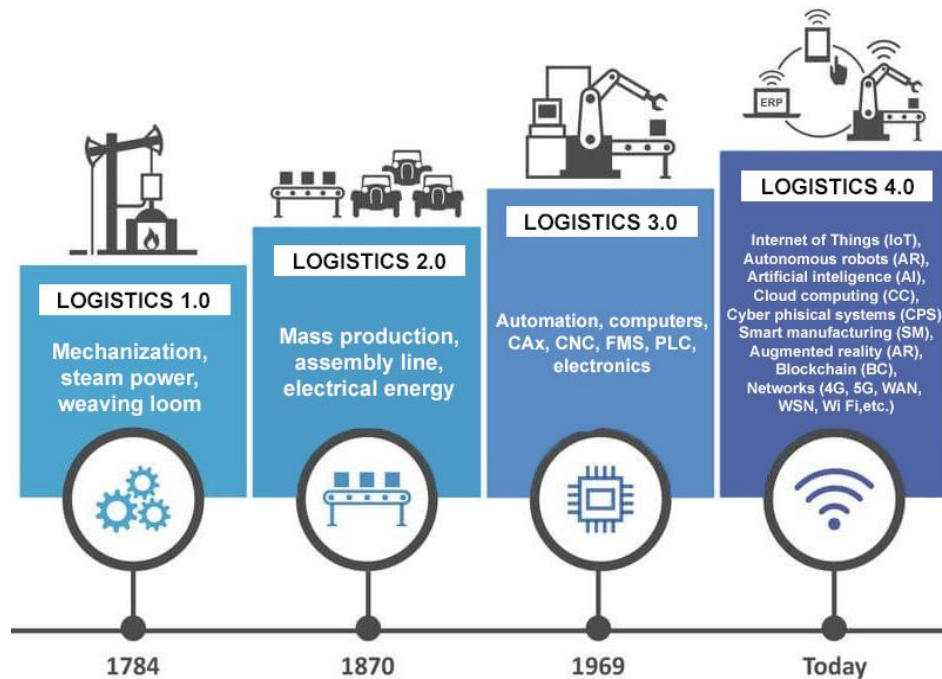


Fig. 1. The stages of logistics evolution from Logistics 1.0 to Logistics 4.0 [17,19]

While many countries are still exploring the development and implementation of the Logistics 4.0 concept, advanced countries have already taken pioneering steps towards Logistics 5.0 [39,60]. This emerging paradigm emphasizes intelligent logistics (IL), smart logistics (SL), smart logistics systems (SLS) and advanced digital technologies (DT). Logistics 5.0 is designed to enhance customized planning, supply chain management (SCM), transportation, distribution, inventory management (IM), warehousing, and more. It prioritizes interconnectivity, integration, digitization, and optimization to create seamless and efficient logistics operations and supply chain (SC).

3. Software Systems and Tools for Logistics

For the efficient realization of logistics and Logistics 4.0, a large number of modern software systems and tools have been developed and are used, which can be classified into the following groups:

- Logistics Databases (LDBs) are used for updating, searching and accessing logistics data;
- Logistics Information Systems (LISs) are used for storing, processing and managing logistics data and information;

- Logistics Management Systems (LMSs) are used for managing logical operations;
- Logistics Decision Support Systems (LDSSs) are used for decision-making in specific logistics operations;
- Logistics Expert Systems (LESs) are used to assess, analyze, provide recommendations and execute changes for numerous logistical and business situations and
- Other software systems and tools for logistics operations.

3.1. Logistics Databases (LDB)

A database for the field of logistics, i.e. logistics database (LDB), enables the updating, quick searching and access to logistics data.

Several examples of developed logistics databases (LDBs) and logistics database systems (LDBSs) are:

- HILDA (Highly Integrated Logistics Database Application), which represents a software system designed to improve the updating and maintenance of the logistics data associated with the jet engine testing facilities [65];
- MLDB (Marine Logistics Database), which represents a database (DB) for maritime logistics designed to integrate data on BD (Big Data) and IoT (Internet of Things) in maritime, such as: port, ship, route, AIS

(Automatic Identification System), trade data, etc. [1,2];

- SHIELDS (Sanctuaries Hazardous Incident Emergency Logistics Database System), which represents a logistics database system and Internet-based information system designed to improve access to critical data, plans, and tools for contingency planning and response situations, developed by National Oceanic and Atmospheric Administration (NOAA) [7], etc.

For the phrase "logistics database", the Scopus citation database has indexed 42 publications in the "Article title, Abstract, Keywords" option and 6 publications in the "Article title" option (as of 31-12-2024).

3.2. Logistics Information Systems (LIS)

Information system for the field of logistics, i.e. logistics information system (LIS), enables the storage, processing and management of logistics data and information. LIS is a software system that unifies logistics and information system (IS). LIS systems also enable the evaluation of actual data and the data creation for planning and forecasting all logistics operations.

The universal structure of the logistics information system (LIS) with four levels is shown in Fig. 2 [17,20].

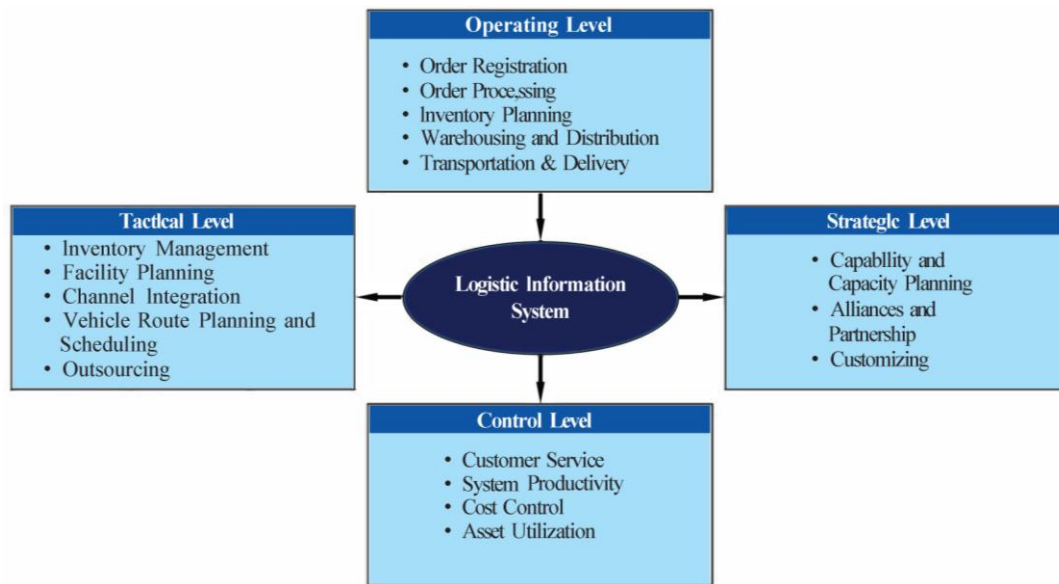


Fig. 2. The universal structure of the logistics information system (LIS) with four levels [17,20]

The structure of each LIS system is developed on a modular principle and consists of the following information systems [17,20]:

- Sales Information System (SIS);
- Purchasing Information System (PIS);
- Inventory Controlling (IC);
- Shop Floor Information System (SFIS);
- Plant Maintenance Information System (PMIS);
- Quality Management Information System (QMIS);
- Retail Information System (RIS) and
- Transport Information System (TIS).

Within the LIS system, in the form of system modules, the following components can be used: Sales and Operations Planning (SOP), Logistics Data Transport (LDT), Logistics Data Warehouse (LDW), Logistics Data Quality (LDQ) etc.

Logistics information systems (LIS) are used in practice in two ways [17]:

1. As a module within a comprehensive and complex firm's total information system (TIS) and/or a complex software system for management and planning of production, such as the software system SAP (System Analysis Program Development). In this case, the LIS represents a subset of the firm's TIS and it is directed to the particular problems of logistics decision making. The LIS system is located within SAP as part of the ERP (Enterprise Resource

Planning) module and is called SAP-LIS (SAP (System Analysis Program Development) LIS (Logistics Information System)) or

2. As a separate system that functions as an independent software and information system.

Several examples of developed logistics information systems (LIS) are [17]:

- CLIS (City Logistics Information System) [34];
- ILIS (Integrated Logistics Information System) [13,56];
- MLIS (Manufacturing and Logistics Information System) [17];
- RLIS (Reverse Logistics Information System) [28,38];
- SLIS (Smart Logistics Information System) [17];
- WLIS (Warehouse Logistics Information System) [62] etc.

All developed variants of Logistics Information Systems (LIS) have wide application in the military industry and warfare, manufacturing, shipbuilding, maritime, aviation industry, automotive industry, agriculture, healthcare, etc. [3,5,15,29,30,43,56,66].

For the phrase "logistics information system", the Scopus citation database has indexed 412 publications in the "Article title, Abstract, Keywords" option and 158 publications in the "Article title" option (as of 31-12-2024).

In addition to logistics information systems (LIS) in the field of logistics, several other similar information systems have also been developed:

- LEIS (Logistics Enterprise Information Systems) [50];
- LIMS (Logistics Information Management Systems) [45];
- LITS (Logistics Information Technology Systems) [22];
- LMIS (Logistics Management Information Systems) [6], etc.



Fig. 3. The main modules of logistics management system (LMS) [51]

Standardized management systems, such as: ISO 9000 Quality Standards, ISO 14000 Environmental Standards or OHSAS 18001 Health and Safety Standards, can be integrated within the LMS system.

Several examples of developed groups of logistics management systems (LMS) are:

- ALMS (Autonomous Logistics Management Systems) [24];
- DLMS (Decentralized Logistics Management Systems) [41];
- GLMS (Green Logistics Management Systems) [67];
- ILMS (Intelligence Logistics Management Systems) [68];
- KLMS (Knowledge-Based Logistics Management Systems) [12];
- RLMS (Reverse Logistics Management Systems) [8];
- SLMS (Smart Logistics Management Systems) [11];
- SLMS (Sustainable Logistics Management Systems) [52], etc.

A large number of software systems and tools for the LMS system have been developed in the world so far, such as: SAP Supply Chain Logistics (URL: <https://www.sap.com/products/scm/supply-chain-logistics.html>), FarEye (URL: <https://www.fareye.com/>), NetSuite Logistic Solutions (URL: <https://www.netsuite.com/portal/industries/transportation-logistics.shtml>), BluJay Logistics Software (URL: <https://www.blujaysolutions.com/>), Quixy's Custom Logistics Software (URL: <https://quixy.com/solutions/industries/supply-chain-and-logistics/>), Optym Logistics Software (URL: <https://www.optym.com/>), Acumatica Logistics Software (URL: <https://www.acumatica.com/>), etc.

3.3. Logistics Management Systems (LMS)

Logistics Management System (LMS) is a software system and/or tools that goods automate and optimise logistics operations (inventory, freight, distribution, warehouse, transport, etc.).

Developed modern LMS systems realize all logistics operations using a large number of new digital and smart technologies based on artificial intelligence [11].

Each LMS system consists of a large number of modules that serve to implement specific logistics operations (Fig. 3) [48,51].

- ➡ Order Management Module
- ➡ Inventory Management Module
- ➡ Freight Management Module
- ➡ Warehouse Management Module
- ➡ Transportation Management Module
- ➡ Manufacturing Module
- ➡ Analytics and Reporting Module

On Fig. 4 shows the conceptual illustration of smart logistics management system (SLMS) [11].

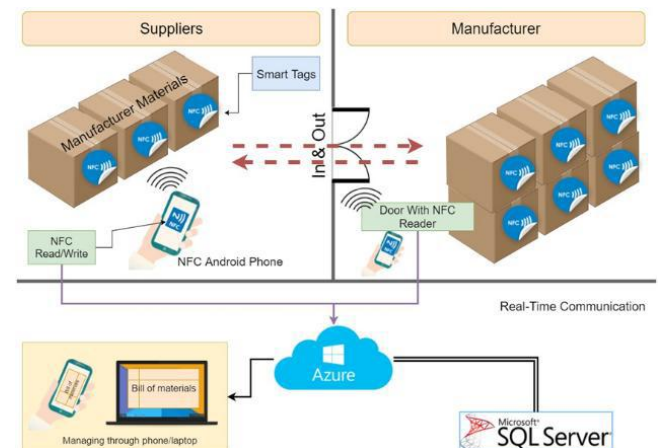


Fig. 4. Conceptual illustration of smart logistics management system (SLMS) [11]

For the phrase "logistics management system", the Scopus citation database has indexed 332 publications in the "Article title, Abstract, Keywords" option and 121 publications in the "Article title" option (as of 31-12-2024).

3.4. Logistics Decision Support Systems (LDSS)

Logistics Decision Support System (LDSS) is a software system that enables effective management by integrating various information about logistics operations within an organization and predicting the potential impact of possible decisions. It is based on a set of procedures used for data processing, information management in the field of logistics, and decision-making, supporting complex and

challenging decisions. LDSS systems for management used different information about logistics operations in organization and predicts the effect of possible decisions, based on methods of complex and hard decision making.

Logistics decision support system (LDSS) is a variant of the decision support system (DSS) applied in the field of logistics. A large number of developed decision support systems (DSS) are also classified based on their application, as shown in the papers [16,47,52,58,63].

Several examples of developed logistics decision support systems (LDSS) are:

- ILDSS (Intelligent Logistics Decision Support System) is a software system for managing and predicting logistics operations, which uses modern intelligent technologies;
- LDNPDSS (Logistics Distribution Network Planning Decision Support System or Decision Support System for Logistics Distribution Network Planning) is a software system for managing and predicting logistics operations, which uses reasoning center (RC) and multi-agent systems (MAS) [61];
- OLDSS (Outsourcing Logistics Decision Support System) is a software system for integrated design and manufacturing of products, developed on the activity analysis of a Lithuanian industry and theoretical assumptions by knowledge economy [4], etc.

For the phrase "logistics decision support system", the Scopus citation database has indexed 21 publications in the "Article title, Abstract, Keywords" option and 8 publications in the "Article title" option (as of 31-12-2024).

3.5. Logistics Expert Systems (LES)

Logistics expert system (LES) is a software system designed to use expert approaches in decision-making to analyze, assess, provide recommendations and execute change for numerous logistical and business situations. Logistics expert system (LES) combines transportation management system (TMS), warehousing management system (WMS), business intelligence (BI), mobile intelligence (MI), consulting intelligence (CI), artificial intelligence (AI), machine learning (ML) and big data (BD) in one software system [36].

For the phrase "logistics expert system", the Scopus citation database has indexed 7 publications in the "Article title, Abstract, Keywords" option and 1 publication in the "Article title" option (as of 31-12-2024).

Based on the very small number of publications on Scopus and the fact that most of these publications are from the period 1986-1990, it can be concluded that the development of these systems is stagnant and that their obvious advantages are being utilized in other newer systems.

3.6. Other Software Systems and Tools for Logistics Operations

A large number of modern software systems and tools for logistics operations also exist, which cannot be classified into any of the previously mentioned groups. A several examples of other groups of software systems and tools developed for logistics operations are:

- LES (Logistics Execution System) or SAP-LES (SAP (System Analysis Program Development) LES (Logistics Execution System)) is a software system and information system specialized in managing an organization's internal logistics, covering all processes from the receipt of raw materials, through storage and internal movement, until the delivery of the final product to shipping areas or consumption points within the organization itself [46];
- LPS (Logistics Planning Systems) is a group of software systems that enable solving tasks from planning in logistics, with several examples of developed LPS systems such as: ELPS (Emergency Logistics Planning System), AELPS (Artificial Emergency Logistics Planning System) [40], etc.;
- LPS (Logistics Production Systems) is a group of software systems designed to support and manage production-related tasks within logistics [55];
- LQMS (Logistics Quality Management Systems) is a group of software systems that enable quality management in logistics [57];
- LTS (Logistics Transportation Systems) is a group of software systems that enable solving tasks from transportation in logistics [54];
- LTS (Logistics Warehousing Systems) is a group of software systems that enable solving tasks from warehousing in logistics [70], etc.

5. Conclusion

In modern industry and society, logistics is a cornerstone of all areas of human activity.

Building on the principles of Industry 4.0, the concept of Logistics 4.0 has emerged. This innovative approach integrates advanced software systems, tools, and intelligent digital technologies (DT) to optimize planning, transportation, warehousing, distribution, and other logistics operations.

Modern business requires greater speed and accuracy during the flow of information within the logistics domain, which can be effectively addressed through the use of software systems and tools (LDB, LIS, LMS, LDSS, LES, etc.) for all logistics operations.

To support the diverse range of logistics activities, numerous logistics databases (LDB) and logistics information systems (LIS) have been developed. These systems provide comprehensive solutions for data storage, processing and management, ensuring efficiency and accuracy in the logistics field.

Modern logistics management systems (LMS) ensure efficient and reliable automation and optimization of all logistics operations including transport, distribution, warehousing, etc.

Developed logistics decision support systems (LDSS) enable the management of logistics operations in an organization, based on various decision-making methods.

Most logistics expert systems (LES) were developed in the period 1980-1990, and its positive advantages are used within the framework of newer systems.

All of the above modern software systems and tools for logistics, compared to traditional ones, use new technologies such as: artificial intelligence (AI), Internet of

Things (IoT), big data (BD), cloud computing (CC), etc. for their intelligent upgrading.

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