Design of an IoT-Based Monitoring System as a Part of Prevention of Thermal Events in Mining and Landfill Waste Disposal Sites: A Pilot Case Study

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***Abstract*— This case study deals with the design of a hybrid system for the prevention of thermal events in mining waste disposal sites and landfills. The overall design, real implementation, optimization, and experimental verification of the functionality of the entire system are described in detail. Both experimental platforms are built on the Internet of Things (long range wide area network (LoRaWAN) and Sigfox) basis and meet the conditions for autonomous long-term on-site monitoring. The data collected are periodically transmitted wirelessly to a database repository, which processes relevant parameters for the operators of dispatching workplaces. The study is focused on a combination of surface and depth measurement methods. The experimental results clearly confirm the functionality of the proposed solutions, which will enable timely interventions and elimination of underground and surface combustions. Thanks to centralized data collection, a unique database has also been created, which can be used for the implementation of prediction algorithms (based, for example, on machine learning or artificial intelligence).**

***Index Terms*— Fire prevention, IoT, IR array, long range wide area network (LoRaWAN), mining waste disposal site, Sigfox, smart metering, temperature measurement.**

I. Introduction

WASTE management is becoming an increasingly important contemporary issue. For example, according to Eurostat [1], 5.2 tons of waste were generated per EU inhabitant in 2018, which is the equivalent of a total of 2.337 million tons of waste. Of this, 38.4% of waste was landfilled and 37.9% was recycled in the EU. According to the available studies conducted worldwide, the annual solid waste production is expected to reach approximately 3.40 billion tons by 2050 [2].

According to Trávníček [3], 59% of all accidents at biogas plants in the EU countries surveyed were related to some type of fire. As for operational requirements, European legislation also places increasing demands on operational requirements [4].

Despite extensive regulations and operational requirements, mining waste disposal site and landfill fires are a very topical issue. This is a global problem that is partly linked to the economic situation of individual countries. This is most problematic in the case of developing countries, where an enormous number of unmonitored and unguarded illegal dumps are created. India, where up to 90% of waste is landfilled in unmonitored areas and where fires often occur, most of which are caused by internal thermal processes, can be used as an example. Although Europe is slowly moving from landfill sites to recycling and reusing of materials, building new landfill sites and monitoring the existing ones is an essential part of the whole waste management process.

By thermal process, we mean the rising temperature of the material of a mining waste disposal site or a landfill. Over time, with increasing temperature, several phases occur, which eventually lead to underground and surface fires.

A mining waste disposal site or landfill mass fire can be defined as a chemical and physical process, the essence of which is the gradual or rapid heating of a flammable substance to at least such a temperature at which decomposition reactions associated with the release of gaseous fumes and heat occur under suitable conditions.

The causes of a mining waste disposal site or landfill fire are very diverse and, in addition to the physical and chemical properties of a certain type of combustible material, are highly dependent on the development and method of depositing the waste or construction of the waste disposal site or the landfill. On the other hand, it is necessary to take into account the facts of direct ignition of fires in landfills caused, for example, during the incineration of various types of garbage and materials, as well as antisocial activities. Knowledge of

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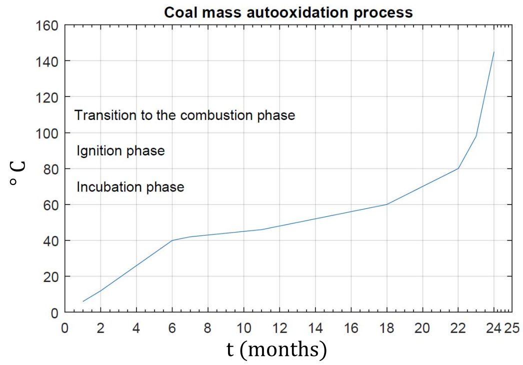

Fig. 1. Idea diagram of the coal mass auto-oxidation process.

the causes of a landfill fire determines not only fire prevention but also the methods of fighting them.

It is known from the technical literature that when a coal substance or material stored in a landfill or a mining waste disposal site is heated to a value of 40 °C–60 °C, spontaneous oxidation is started, and the temperature rises to the value of ignition of waste or organic substances.

The self-ignition of the material deposited in a landfill or a mining waste disposal site is subject therefore to a gradual oxidation of the deposited material, or also admixtures (pyrites) with sufficient air access. The oxidation process generates heat, which accumulates due to the low thermal conductivity of the deposited material as the temperature of the material rises. At the same time, dangerous gases are formed, especially carbon monoxide (CO) and methane.

A. Limit Values

By limit values, we mean reaching the value when remediation intervention is necessary. If the increase in value increases, unacceptable conditions will be created, leading to the formation of explosive gas concentrations, hazardous concentrations of toxic gases, and the risk of an underground and subsequent surface fire.

For the aforementioned reason, long-term continuous measurement of the thermal processes taking place, especially temperature, and its evaluation are necessary. Technological procedures must be developed to measure the chemical processes taking place within the deposited materials, especially for the recognition of reaching the limit values and we consider that they should be implemented as soon as possible.

The temperature condition is the most important measure for assessing the hazards of thermal processes in the monitored area of landfills or mining waste disposal sites. The previous text describes the process of heat accumulation due to auto-oxidation processes. However, it should be noted that the thermal process in the interior of landfills or mining waste disposal sites can also occur as a direct initiation, for example, as a result of surface fires either started intentionally (burning of woody plants, antisocial behavior when burning cables) or as a consequence of accidents—surface fires of objects or trees (shrubs, trees) located here. Fig. 1 shows the temperature rise curve.

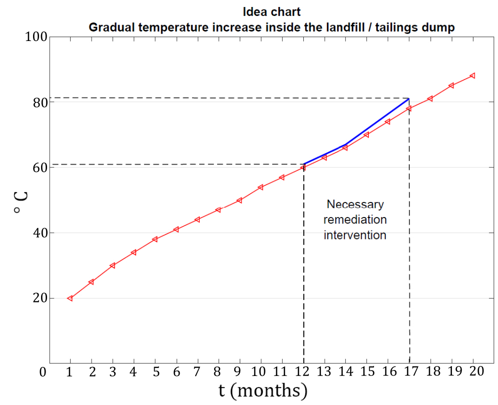

Fig. 2. Temperature rise idea chart—gradual temperature increase inside the landfill/tailings dump.

From this curve, several ranges of temperatures ensue, which characterize the hazardousness of thermal processes. During the temperature rise, the following measures can be implemented according to the specific situation, the aim of which is as follows.

1) For the prevention of the occurrence or continuation of thermal processes, it is necessary to implement appropriate measures when temperatures do not exceed 40 °C–50 °C.
2) For the prevention of a sharp increase in thermal activity, remediation is necessary until temperatures reach 70 °C–80 °C.
3) For the prevention of the occurrence of underground fires, immediate remediation is necessary at maximum temperatures of 130 °C–150 °C.

The necessary evaluation of the long-term development of temperatures in the monitored locality is one of the criteria. The time period when the temperatures rise and the steepness of the increase in these temperatures are assessed. The periodic increases and decreases, wherein the prognosis of development is practically identical with the x-axis, are special cases. The idealized graphs are shown in Figs. 2 and 3, with appropriate comments.

The character of the curve: gradual increase in temperature in the range of 10 °C per two and a half months. There is relatively enough time (in the order of several months) for the preparation and implementation of remediation measures.

The character of the curve: sharp rise in temperature in the range of 10 °C per one month. There is little time for the preparation and implementation of remediation measures—they must be used in about two months.

B. Negative Environmental Impacts

At present, when there is an increasing emphasis on improving the quality of the environment, burning mining waste disposal sites (but also municipal household waste sites) is a significant negative factor and a source of pollution in the wider environment.

During the ongoing thermal processes, a number of risks of varying degrees of danger arise, some of which directly endanger people's lives. The following text deals with the most

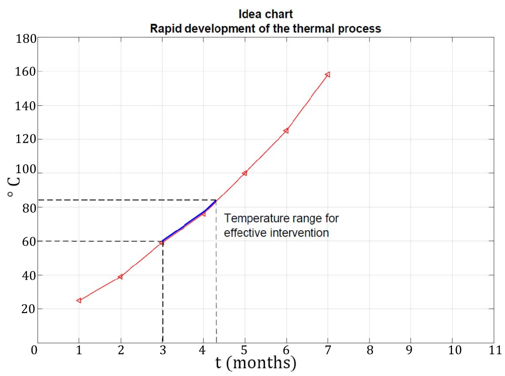

Fig. 3. Temperature rise idea chart—rapid development of the thermal process.

serious risks arising from the existence of a burning landfill or mining waste disposal site.

1) Heat Development: By burning the flammable parts of a landfill or a mine waste disposal site, considerable heat will be released. This purposelessly escapes into the atmosphere and contributes to the disturbance of the natural balance in the location. The amount of heat released during many years of thermal activity is enormous and occurs in the orders of millions of megajoules. For orientation purposes, it can be stated that when burning down a space with a volume of 1 million tons of deposited waste in which there is about 30% content of flammable substances and 75%–80% combustion efficiency, about 250 000 tons are burned (coal, sulfur, and organic waste).

2) Release of Toxic Substances: Each mining waste disposal site or landfill site contains a disparate mixture of mostly carbonaceous rocks, coal, as well as domestic and industrial waste, which was also taken uncontrollably to slag heaps during the commercial operation of the mining company. In the past, mining waste disposal sites were often used as landfills for various kinds of waste from other companies located in their vicinity. Despite legislative measures, waste was dumped, often illegally, and therefore there are no records or documentation of its nature and quantity.

During fires, not only the coal substances burn but also all organic substances and, in extreme cases, illegally stored chemicals.

Even if the mining waste disposal site does not contain other kinds of waste, the thermal processes activate the chemical components that are part of the rocks and release them either into the air or they are washed off by water with a subsequent contamination of surrounding watercourses and groundwater. Hazardous substances can be discharged into the environment such as sulfur, mercury, arsenic, and other heavy metals. Also, carcinogenic aromatic hydrocarbons and, in some cases (e.g., Kateřina Coal Mine, Radvanice, Czech Republic), even radioactive substances can be released into the environment.

The production of highly toxic CO, which arises as a result of imperfect combustion in the absence of oxygen, is the biggest and most extensive danger, with the occurrence of lethal concentrations, especially in the immediate vicinity of a discharge duct on burning mining waste disposal sites or landfill sites. This is evidenced by the frequent findings of dead small animals (hares, pheasants, etc.). Hydrogen sulfide (H_2S) is another highly toxic gas that can be released into the atmosphere during this combustion process.

3) Development and Spread of Fine Dust: During thermal reaction, the surface dries out or even burns down, creating a fine dust that is easily moved by air movements to considerable distances from the mining waste site. The previous point (2) states that various toxic substances are formed which, among other things, bind to this fine dust.

The possibility of increased radioactivity is another danger associated with the transfer of fine parts of dust. Some black coal deposits are accompanied by uranium-containing rocks. During the thermal process, the dust generated is contaminated.

4) Formation of Burned-Down Areas Inside a Mining Waste Disposal Site or a Landfill Site: As organic matter burns, the volume in the area decreases. Usually, there is a gradual decrease in the surface as the burning-down process proceeds. In some cases, in places where a large amount of combustible substances have been accumulated during the storage of material, free spaces (caverns) are created after their combustion. These caverns are very dangerous. There is a lethal threat of falling through into this area while the material is burning down and the surrounding environment is hot. Also, falling through into already cooled open spaces is highly dangerous.

5) Start of a Surface Fire: With a developed thermal process inside a mining waste disposal site or a landfill site, there is always a risk of a transition to a surface fire. The old mining waste disposal sites are often forested, with relatively dense vegetation. In some cases, various buildings are built here, either directly on the mining waste disposal site or in its immediate vicinity. Ignition of vegetation or surface structures will then cause significant damage with long-lasting consequences (new planting of vegetation).

C. Necessity of Monitoring Thermal Processes

It follows from the aforementioned facts that thermal processes, as a result of mining waste disposal site and landfill site negligent management, have a very negative impact on the environment and represent an immediate threat to property and human health. Therefore, it is necessary to monitor these phenomena in the long term and to ensure that the site management is informed about exceeding the given limit states. Subsequently, remediation measures are used to prevent the spread of thermal processes to areas where there are buildings or other areas intended for leisure activities.

The quantities monitored include temperature, which characterizes the extent of the thermal process, its location, and direction of propagation. In the vicinity of buildings or other areas that are freely accessible, special measuring probes are installed, equipped with temperature sensors, and, on the basis of the measurements, management then evaluate the data obtained. In the event of exceeding the limit values set, an immediate remedial action is taken to limit or stop the effect of thermal events.

Other important quantities needed for long-term monitoring include concentrations of hazardous gases such as

CO and CH_4. These gases are also a consequence of thermal processes and occur in old mining waste disposal sites and municipal solid waste (MSW) landfill sites. CO is very dangerous for humans, since there is a risk of serious damage to health or even death if a certain concentration is inhaled. While these dangerous concentrations are only found in certain locations in mining waste disposal sites, this risk must not be underestimated.

It should also be noted that thermal processes in the inner space of mining waste disposal sites or landfill sites are highly unpredictable and irregular, both in their area and intensity. Thermal monitoring is sufficient with a resolution of several degrees Celsius. Accurate measurement with an accuracy below 1 °C is unnecessary for common practice.

The Moravian-Silesian Region, especially the Ostrava and Karviná districts, have been and remain the most important locality for hard coal mining, and the mining waste disposal site management is a direct result of this activity. The autoxidation processes of coal residues found in mining waste disposal sites and slag heaps is a negative phenomenon and is very dangerous in the management of these mining waste disposal sites. In many cases, heat accumulates, resulting in an underground fire of a greater or lesser extent. In the past, a large part of the mining waste disposal sites was affected by thermal processes, and some have remain active. A suitable way of monitoring the temperatures in the depth of the mining waste disposal site, including the appropriate instrumentation, is needed to determine and locate the area where the thermal process could begin or exists. In general, it can be said that thermal processes and their consequences have to be monitored and evaluated very carefully for a considerable period, not only in the areas of old mining waste disposal sites and slag heaps but also in the areas of industrial landfill sites.

II. State-of-the-Art

As described above, the world's total waste production is growing and needs to be further processed, with landfilling being one of the solutions. Today's modern technologies, however, allow us to better monitor these landfills and prevent adverse events, such as landfill or mining waste disposal site burning. Nevertheless, Mabrouki et al. [5], Reddy et al. [6], and Bhoir et al. [7] monitor other parameters than just temperature, such as methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2).

Ramesh et al. [8] focused on monitoring soil and water pollution in the Pettipalam area in Thalassery (India). This is an area polluted with municipal waste and feces. The authors devised an Internet-of-Things-based monitoring system to detect the quantitative measure of the acidity or basicity of aqueous or other liquid solutions (pH), conductivity, dissolved oxygen, turbidity, etc. They expect the results obtained to help with the initiative for the restoration of land and water resources in the area.

He et al. [9] describe a landfill slope monitoring method based on electroacoustic sensors that are part of the wave guides placed in the landfill body. The response in the frequency domain was monitored. In the data measured, the manifestation of an event characterized by high amplitude caused by friction and collision between the gravel and the waveguide is evident when a material slide occurs. The authors verified this method in laboratory conditions using the appropriate test equipment.

In contrast, Savla et al. [10] present an IoT system using the machine learning methods. They represent a smart module, which consists of several parts, where the first part captures the area with a camera and takes pictures, which are further processed by a neural network. Other parts are mainly used to collect accompanying data (combustible gas and smoke detection sensor, CO and methane detection sensor, ammonia sulfide and benzene vapor detection sensor, liquefied petroleum, methane, butane, and LPG sensor). Based on these data, the so-called air quality index is subsequently evaluated.

In this work [11], Smoliński et al. focused on the methodology of monitoring thermal processes in mining waste disposal sites and changes in emissions of polycyclic aromatic hydrocarbons (PAHs). Two mining waste disposal sites that were not reclaimed were monitored, one that is partly reclaimed and partly in operation. A relationship between PAH emissions and high temperatures during material burning in nonreclaimed mining waste disposal sites has been observed. Most reclaimed mining waste disposal sites are characterized by temperatures below the level of thermal process.

Mahmood et al. [12] focused on examining satellite images (a total of 66 images) of the area around the MSW landfill in Gujranwala, Pakistan, taken by four satellites. At various times of the year, for a period of three years, bio-thermal effects were observed around the landfill. A positive correlation between the extent of the affected zone and the amount of MSW deposited in the landfill was verified.

The monitoring of thermal processes in tailings dumps from the coal mines of the Upper Silesian Coal Basin is presented in [13]. The methods of point measurement and remote sensing were compared. Both the methods are suitable for identifying material combustion inside mining waste deposits. Because the data obtained from the individual methods differ, it is, therefore, appropriate to use a combination of the results of both the methods.

In this work [14], Surovka et al. deal with the monitoring of thermal processes in mining waste disposal sites in the Ostrava region. Hedvika mining waste site was chosen for this article. Methods of remote sensing using a drone equipped with a thermal camera were used and, at the same time, samples were taken from two sampling points. A demonstrable effect of thermal processes on surface vegetation was observed.

Pies et al. [15] focus on the development, construction, and testing of a special autonomous system for long-term monitoring of environmental signals, which are crucial for proper functioning of heat collection technology in thermally active mining waste disposal sites. They used their own autonomous data collection system around a heat exchanger located in a thermally active mining waste deposit. In addition to temperatures, the system also uses gas detectors (CH_4, CO), and air temperature and humidity. The data obtained are stored in a database after having been statistically processed.

Abu Qdais and Shatnawi [16] describe temperature monitoring of a landfill surface in northern Jordan using satellite imaging. An artificial neural network, which had the task of simulating and predicting the future development of the landfill surface temperature, was devised to evaluate the images acquired. Verification of the results showed a good correlation between the predicted and subsequently measured landfill surface values. This method of using satellite imaging is becoming ever more widespread and, for example, Nazari et al. [17] and Islam et al. [18] deal with it.

However, satellite imaging has several major disadvantages, including, above all, time constraints—as data are collected only when the satellite being used flies over the site. For this reason, some authors have begun to use their own unmanned aerial vehicles (UAVs) for imaging the designated area of the landfill. For example, the work [19] describes the use of UAV for landfill monitoring, where temperature, CO, CH_4, and humidity are monitored. Based on the data measured (based on thermal infrared (TIR) images), a temperature map of problematic places in the landfill is created. The same approach is also used in [20] when, in addition, local sensors situated directly at the landfill (for example, subsurface boreholes) are also used to obtain data.

Yadav et al. [21] use wireless sensor networks and fog-computing to monitor the condition of surface mine slopes. They use their own sensor modules for measurements using time-domain reflectometer (TDR) sensors in the form of cables. Data are transmitted via the long range wide area network (LoRaWAN) technology. The data are preprocessed in the fog layer, which is formed by LoRa/internet gateways, thereby reducing the amount of data processed on the cloud. This approach is similar to edge-computing.

Zhang et al. [22] describe the monitoring of underground coal mines by means of an UAV. Various methods are used for location tracking, and according to the results, on-demand precise tracking (OPT) appears to be the most effective method. The authors conducted field experiments directly in the underground of a coal mine.

The advantages and disadvantages of the monitoring systems of environmental quantities are summarized in Table I.

Based on the state-of-the-art result, it was found that there is currently no comprehensive wireless monitoring system available that would provide a comprehensive measurement of thermal events at landfill sites or mining waste disposal sites, both on the surface and in depth probes. There are various solutions for remote observation via drones or satellites, but these systems are not suitable for continuous monitoring, there are also systems for measuring surface and subsurface temperatures, but these are always separate solutions that are not able to concentrate and process data within one system. It was also not found that a comprehensive monitoring system based on the use of low-power IoT technologies would be available.

III. Materials and Methods

The determination of surface and depth temperatures is the basic precondition for monitoring and evaluating the thermal activity of mining waste disposal sites or municipal landfill sites. In current practice, the extent and intensity of the thermal process are evaluated as follows.

1) *Visual Observation:*
   The heat-affected surface of the mining waste or the landfill waste makes its presence felt especially in the winter, where there is no snow over the active area. During an advanced endogenous fire, the smoke comes to the surface through cracks. A strong aromatic odor serves as another strong indication. The continuing stage of burning is also indicated by the withering of vegetation on the surface.
2) *Surface Temperature Measurement:*
   Measurement of the temperatures of the surface layer of the mining or the landfill waste site is used to assess the extent of thermal processes in terms of area. Infrared thermometers are mostly used, wherein a dense network of points is measured, and isolines of the temperatures are determined graphically. For larger and inaccessible terrains, aerial imaging with color marking of areas with elevated temperatures is used.
3) *Depth Temperature Measurement:*
   To accurately determine the area on the surface of the mining or the landfill waste site, and in particular to determine the depth range, depth measurement is performed. The temperatures are sensed in steel probes, which are installed to the required depth in a specified sensor network. To measure temperatures, conventional mercury (alcohol) thermometers, thermocouple probes, or probes equipped with digital temperature sensors (SMT160/30, DS18B20) are used together with a microprocessor-based evaluation unit.

As already mentioned, temperature measurements (whether surface or in depth probes) using classical methods are performed manually by means of mercury (alcohol) thermometers, which are let down into special depth probes. Subsequently, a visual reading of the values measured and their writing for later processing using a personal computer (PC) is performed. The second option includes the use of thermocouple probes and reading the value measured on the display of the measuring instrument. Again, the values measured must be written manually for later processing using a PC. These methods of monitoring temperatures inside mining dumps have a number of disadvantages. The most important ones are as follows.

1) Inaccuracy in the visual reading of the values measured, especially in the case where, from the moment of pulling out the thermometer (especially located at a greater depth) to the moment of visual reading, a certain time elapses during which the temperature on the scale drops. This inaccuracy can be great in winter when the air temperatures are low.
2) With the existence of high temperatures in the mining dump space, it is very difficult to pull out the mercury thermometers. The steel wire or chain which they are attached to is hot—there is a risk of burns. Pulling out the thermometers can cause them to break; mercury thermometers, in particular, are dangerous at this moment.
3) The length of time to accurately locate the thermometers and which must be left at a specific level for a period of time before their protective case heats up and the temperature recorded.

TABLE I
SUMMARY TABLE OF THE MONITORING SYSTEMS

Author	Monitoring Locality	Quantities Monitored	Monitoring Method	Wireless Transmission	Two-Way Communication	Low Power	Advantages/Disadvantages
[5]	Landfill waste site	CH_4, CO_2, O_2, N_2, CO, H_2	surface	Yes	Yes	No	A: Low cost, Multi-gas sensing D: Wi-Fi, GSM, Arduino based, low cost sensors
[6]	Landfill waste site	CH_4, CO_2, CO, Temperature, Humidity	surface	Yes	No	No	A: Low cost solution, SMS alarm, multi sensors D: Wi-Fi, GSM, no low power
[11]	Mining waste site	PAHs, Temperature	surface	No	No	No	A: monitoring a large area, measuring high temperatures D: Price, IR camera, image processing
[13]	Mining waste site	Temperature	surface, underground	No	No	No	A: monitoring a large area, ; D: Price, image processing
[14]	Mining waste site	Temperature, CO_2, CO, SO_2, PAHs	surface	No	No	No	A: Measurement of a large number of quantities, Chemical analysis, Thermal imaging of the territory D: Price, image processing, Sampling points needs, Manual sampling
[15]	Mining waste site	Temperature, CO, CH_4, humidity	surface, underground	Yes	Yes	Yes	A: Autonomous system, Low Power, Modularity, Robustness, multi sensors D: Price, Battery operation, cable line
[16]	Landfill waste site	Temperature	surface	No	No	No	A: Use of artificial intelligence, size of scanned area D: Price, surface measurement only, time limited data collection
[17]	Landfill waste site	Temperature	surface	Yes	No	No	A: Large area monitoring, multi-landfill monitoring, facility security D: temperature only, surface measurement only, time-limited data collection
[16]	Landfill waste site	Temperature	surface	No	No	No	A: Use of artificial intelligence, size of scanned area D: Price, surface measurement only, time limited data collection
[19]	Landfill waste site	Temperature, CO, CH_4, humidity	surface	Yes	No	No	A: Large number of quantities sensed, data transfer to GIS, use of UAV, NIR D: UAV price, bluetooth for data transfer, image processing
[20]	Landfill waste site	Temperature, CO_2, CH_4	surface, underground	No	No	No	A: Combination of several approaches, use of UAV, TIR, local boreholes D: Price, missing wireless data transmission

Temperature monitoring using both the aforementioned measurement methods must, in addition to the already mentioned shortcomings resulting from their design, also deal with the following negative facts.

1) In many cases, it is necessary to perform thermal monitoring inside ground formations, the shape or location of which does not allow or considerably complicates the installation of measuring steel probes. These are mainly steep slopes and areas with impassable or dangerous cover, such as muddy environments (sludge beds, etc.).
2) The localities monitored are mostly outside the residential zones, mostly quite far from common buildings and infrastructure. The access can be difficult and often impossible in the winter months with higher snow cover.
3) Antisocial persons move in the localities monitored. The measuring probes are often intentionally damaged or stolen. Due to their movement, the safety of measuring staff and the protection of vehicles, which have to be parked close to the site but out of sight of the measuring site, must be addressed.

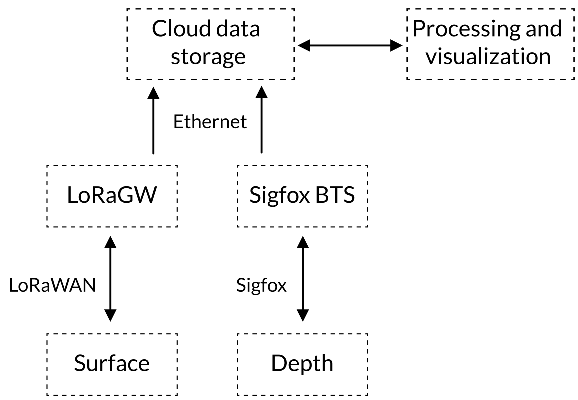

Fig. 4. Overall monitoring system block scheme.

The above-mentioned methods of manual temperature measurement are associated with the disadvantages and risks described. Therefore, they are currently being abandoned and replaced with special autonomous systems that ensure long-term monitoring of the given quantities, including the transmission and processing of the data measured. The basic block diagram of this system is shown in Fig. 4 and is described in more detail in the following text.

A. Surface Temperature Measurement

The measurement of surface temperature in the area of monitoring thermal processes serves primarily to determine the extent and location of the actual thermal process in a large area of the mining waste deposits. Due to the need to measure or monitor a large area for a long time, contact-based measurement methods cannot be used in this case. Thus, contactless temperature measurement methods based on the principle of sensing the intensity of infrared radiation from the measured surface are preferably used. Handheld pyrometers or infrared thermocouples can be used for quick information on the surface temperature of the mining waste disposal site. With the help of these devices, we acquire information about the temperature at the specific measuring point. As already mentioned, in the field of monitoring thermal processes on old mining dumps, it is necessary to monitor large areas. Infrared or thermal imaging cameras are used for these measurements. Thermal imaging is a contactless method of monitoring the temperature of a large area in a single measurement.

B. Temperature Measurement in Depth Probes

Surface temperature measurement methods have been described above. This measurement provides us with visual information about the area of thermal events in the affected area. However, from the results, we are not able to determine how the thermal process takes place inside the affected area. It is the knowledge of the depth course of the thermal process that is very important for the assessment of its further development and the implementation of possible remedial interventions to prevent damage to property and human health.

For detailed knowledge of the distribution of the thermal process inside the mining or the landfill waste deposits, temperature monitoring is performed using special measuring

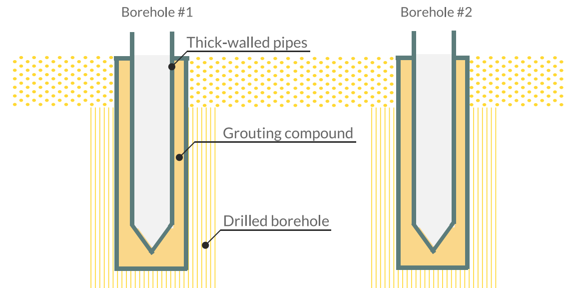

Fig. 5. Depth measurement probes.

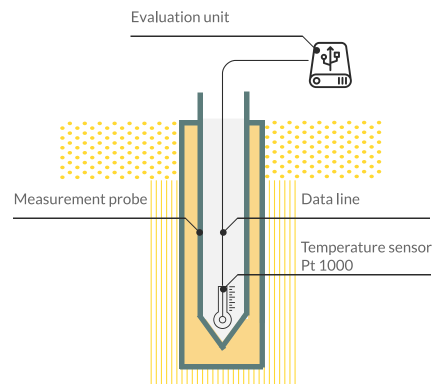

Fig. 6. Example of mechanical measurement using a mercury thermometer and a thermocouple probe.

probes. The probes are most often constructed of thick-walled steel tubes with a diameter of about 50 mm and a thickness of 2–4 mm. At the end of the probe, the tube ends with a tip for easier ramming to a specified depth. As standard, the measuring probes in question have a length of 1.5 m and, when measuring at greater depths (up to 15 m) is required, they are stacked on top of each other using special couplers. The probes are installed manually either by ramming into a designated place or by means of a drilling technique, where a hole is drilled to the required depth; the probe is inserted there and the surroundings are grouted. See Fig. 5 for example of installation of a special measuring probe.

Commonly available alcohol, or previously mercury, mechanical thermometers are mostly used for manual temperature measurement in the aforementioned measuring probes. The temperature measurement range is up to 120 °C or 400 °C, depending on the range of the thermal process. The thermometers are placed in metal housings (usually aluminum) or protective grilles. They are let down to a specified depth by steel cables or chains. The basic disadvantages of using conventional thermometers have been described above.

In addition to conventional mercury or alcohol thermometers, electronic measuring systems based on the use of Pt100 or Pt1000 resistance sensors and/or thermocouple measuring sensors are used. The sensor itself with signal conductors is let down to the specified depth and a diagnostic evaluation unit is connected to the output terminals (see Fig. 6).

The accuracy of the measured quantities is determined by the properties of the sensors used. The parameters of the individual sensors used are given in their datasheets. For example, K-type thermocouples were used for depth probes,

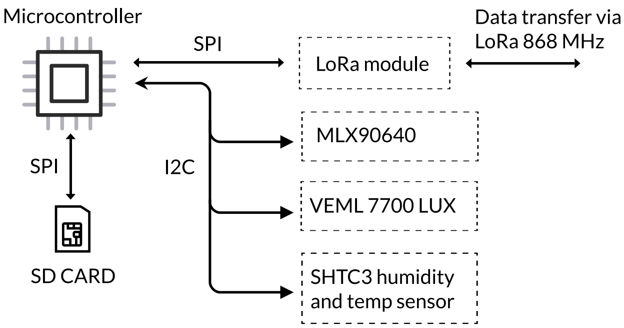

Fig. 7. Schematic of the sensor module used for surface measurement.

for which the manufacturer states accuracy class 1, which means ±1.5 °C between −40 °C and 375 °C [23]. The thermoelectric voltage from these thermocouples is measured by a special MCP9600 analog frontend, whose datasheet also indicates an accuracy of ±1.5 °C [24].

C. Experimental Platform for Remote Landfill and Mining Waste Sites Surface Temperature Reading

To measure the surface temperature of the monitored area, the team developed an experimental sensor module equipped with a LoRaWAN communication module. The main part of the experimental equipment comprises an MLX90640 sensor [25], which serves as a temperature sensor with an infrared matrix (32 × 24 values) providing a range from −40 °C to 300 °C (with a deviation of 1 °C in the entire measuring scale). The system is equipped with an SHTC3 sensor [26] for measuring ambient climatic conditions (temperature and relative humidity). A VEML7700 sensor [27] located on the top of the module forms also an essential part; it is used to monitor the illuminance. The complete schematic of the proposed system can be seen in Fig. 7.

All the above-mentioned sensors are communicating with the microcontroller via I^2C bus and they are placed together with the LoRa module and secure digital (SD) card on the one printed circuit board. It creates a compact measuring system, which can be deployed anywhere in the landfill disposal site.

The entire system has undergone a series of previous tests, which were presented in more detail at an international conference. The initial functionality of this concept was verified and presented at the international conference [28].

The aforementioned robust sensor system is directly connected to the microcontroller, which controls all data acquisition, periodic data storage to the card and sending relevant results through the LoRaWAN communication interface.

The data are simultaneously written to the SD card at 1-min intervals. The system thus creates an unprocessed database of raw data, which is backed up for later evaluation at a station with higher computing performance. For centralized collection using the LoRaWAN technology, it is necessary to reduce and filter the data; the system itself is able to transfer only 24 out of a total of 32 values monitored due to technological limitations. The complete schematic of software (SW) data processing is shown in Fig. 8

A MatchX MX1701 LoRaWAN gateway, the parameters of which can be seen in Table II, is used for data transfer.

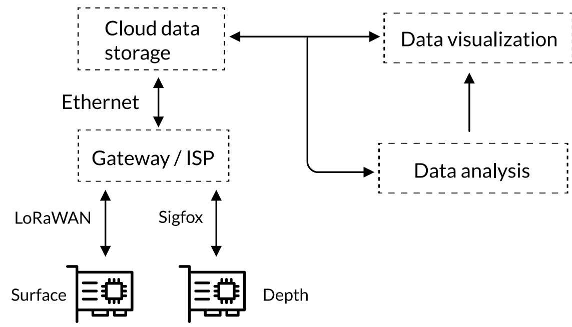

Fig. 8. Software data processing schematic.

TABLE II
TECHNICAL PARAMETERS OF THE MATCHX MX1701 LORAWAN GATEWAY

Band	863 – 873 MHz
Special RX	865 – 867 MHz
Maximum Conducted Power	+27 dBm
LBT	EUROPE
SF	7-12
Certification	EN 300200 EN 301489
IP Rating	IP65
Power supply	24 V POE
Maximum LoRaWAN packet sensitivity	-143 dBm

The data are then sent and collected centrally in the InfluxDB (Open Source Time Series Database). A Grafana software tool is then used for data visualization and analysis. However, it is necessary to link the service with an existing database that contains the necessary data. Grafana also provides basic data analysis tools.

Fig. 9 shows a compilation of photographs from the real installation at the landfill waste site for surface temperature measurement. The top part of the image shows a view of the entire installation, including the monitored landfill waste site in the background. The middle part shows a detail of the actual installation and mounting. The bottom part of the picture shows the three sensor units mounted in an IP54-compliant enclosure. Each sensor unit contains an MLX90640, a VEML 7700 LUX, and an SHTC3 humidity and temperature sensor. Multiple sensor units were required to fully monitor the landfill surface due to their limited resolution and area coverage.

The system described in Fig. 9 is powered directly by the electrical grid. However, the proposed device allows being powered by a battery (3000 mAh), where the lifetime of the device is calculated to be 330 days at an average consumption of 0.3 mAh. The average consumption of the device is calculated from sleep mode (0.26 mA) and data transmission + measurement (125 mA). The following equation was used to calculate:

$$ac = \frac{(\text{Cons1} \times \text{Time1}) + (\text{Cons2} \times \text{Time2})}{\text{Time1} + \text{Time2}} \tag{1}$$

Fig. 9. Real installation of a prototype for measuring landfill surface temperature. The top part shows a view of the whole installation with landfill, the middle part shows a detail of the prototype installation, and the bottom part shows used sensors with adequate IP protection.

where

- ac is the average consumption;
- Cons1 is the consumption during data measurement and transmission;
- Time1 is the measurement and transmission time;
- Cons2 is the average power consumption during sleep mode; and
- Time2 is the device time in sleep mode.

D. Experimental Platform for Remote Reading of High Temperatures in Boreholes

For remote measurement of high temperatures in boreholes, the team developed an experimental sensor module equipped with a Sigfox communication module. The actual design of the sensor is based on strict requirements for simplicity of implementation, very low energy consumption, and the possibility of multichannel measurement. The basis of the system is formed by an MCP9600 integrated circuit which directly converts the thermoelectric voltage into degrees Celsius. The block diagram of the wireless sensor is shown in Fig. 10.

As already mentioned, the core of the system is formed by the MCP9600 circuit. It is an integrated converter of thermoelectric voltage to degrees Celsius manufactured by Microchip. The support of a wide range of standard thermocouple types is its main advantage. It works in the supply range of 2.7–5.5 V, and the communication with it takes place via two-wire bus I^2C. As standard, it is delivered in an more thin plastic quad flat (MQFN) case. The MCP9600 circuit itself allows connection of one thermocouple. It follows that for multichannel measurement, it is necessary to use several pieces of circuit, the number of which depends on the number of measuring points. Based on the requirements of the monitoring site, the team designed a four-channel wireless sensor that uses four pieces of the MCP9600 circuit.

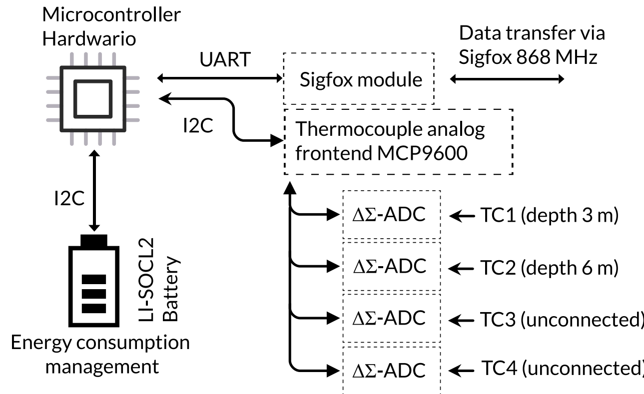

Fig. 10. Block diagram of the IoT sensor module used for depth measurement.

Each of the thermocouples connected generates thermoelectric voltage fed to the MCP9600 input through a low-pass RC filter, which serves to suppress line interference. An 18-bit sigma–delta AD converter, which uses internal voltage references, is used in the circuit to digitize the signal. The circuit has its own ambient temperature sensor, which is used to compensate for the cold end of the thermocouple.

The Hardwario Core Module motherboard with an STM32L083CZ microprocessor (module with a 32-bit microcontroller) is the centerpiece of the system. The core module provides I^2C communication with all MCP9600 circuits and seamless universal asynchronous receiver-transmitter (UART) communication with the Sigfox module. The microcontroller also includes an integrated real-time clock (RTC), which the system uses to plan the measurement time accurately. The universal serial bus (USB)/UART converter, which facilitates writing a program to the microcontroller, is the last but no less important part of the board.

The entire platform is powered by a primary lithium thionyl chloride batteries $(Li\text{-}SOCl)_2$ battery with a capacity of 19 Ah. It is connected to a buck–boost DC/DC converter, which has an output voltage of 3.1 V and provides power to the entire wireless sensor module.

Monitoring of the battery status is ensured by applying its voltage to the input of a 16-bit AD converter of the microcontroller using a voltage divider. The voltage divider is connected via a transistor, which ensures its disconnection when the battery is not measured.

As described for the surface temperature measurement system, the 4 MCP9600 integrated circuits are, along with other supporting electronics, located on a printed circuit board that is a superstructure for the main Hardwario microcontroller board, as shown in Figs. 10 and 11.

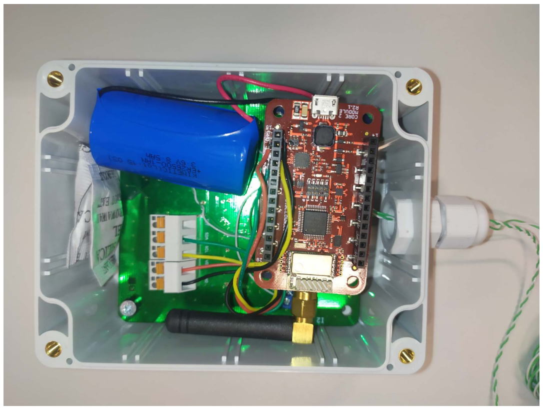

Fig. 11. Photographs of the IoT sensor module prototype used for depth measurement.

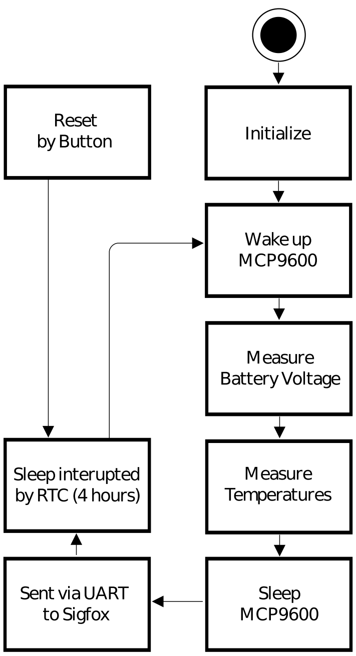

Fig. 12. UML diagram of the SW part of the IoT sensor module.

Fig. 11 shows a prototype of the sensor devised.

The firmware for the sensor module is designed to be event-driven. The main task is started based on an RTC-triggered interrupt. This time interval can be set as desired. In the case of the pilot measurement, it was a 4-h interval. A similar system is also mentioned in [29] and [30]. In the main task, wake-up and setting of all MCP9600 circuits is performed gradually via the I^{2}C bus. Furthermore, the battery voltage is measured using an internal analog-to-digital conversion (ADC). Finally, the high-temperature registers in all the MCP9600 circuits are read sequentially together with the cold end temperature from one selected MCP9600 circuit. Once the reading is completed, the system immediately puts all unnecessary circuits to sleep.

The values read are then transferred to individual bytes and sent to the Sigfox module via UART. The block diagram of the SW part of the wireless sensor is shown in Fig. 12.

The actual reading of the data from MCP9600 is conducted using four functions, which are called in a fixed order—MCPStart, MCPGetStatus, MCPMeasure, and MCPStop. These functions are used in the blocks shown in Fig. 12.

Fig. 13. Deployment of the module devised when monitoring at the Heřmanice mining dump.

MCPStart making entry into the configuration register of the device, which is used to set the parameters such as its operating mode and resolution of the hot and cold end AD converter, is the first function called. When making the entry, the device is set to a normal operating mode with the highest possible resolution.

The MCPGetStatus function, after converting the circuit to normal operating mode, periodically measures the thermocouple temperature and then stores the data. This function checks the bit in the device register status, which indicates successful completion of a new measurement and storage of the data. It then returns the value of this bit, i.e., false if the measurement is in progress and true for completed measurement with the data prepared. The function is called cyclically until it returns a true value and the program can continue to the next function.

The MCPMeassure function is used to read the parameters from the available data. It works in two steps, as the value is 16 bits in size. The microcontroller unit (MCU) requests the first eight higher bits first and, subsequently, the remaining eight lower bits. The two messages are then combined and converted into temperature using the formula below. After reading the temperature, the bit is reset to zero in the status register, which indicates a completed measurement, so that the next measurement does not read the original data. The function then returns the resulting temperature in the double form. Fig. 13 shows the module while monitoring at the Heřmanice mining dump.

IV. Results

Both the proposed systems were devised for long-term autonomous monitoring of thermal processes in mining and landfill waste sites. The staff of the areas monitored do not have to perform on-site measurements, which are often both time-consuming and dangerous. The data measured are archived in a cloud storage in the form of a MySQL database. The database also serves as a source for subsequent data visualization. The actual visualization is implemented using the Grafana software platform.

In order for the responsible employees to be immediately informed, sending of notifications is implemented in Grafana when the value of the measured quantity set is exceeded. Notifications can be sent via email or short message service (SMS) at any time.

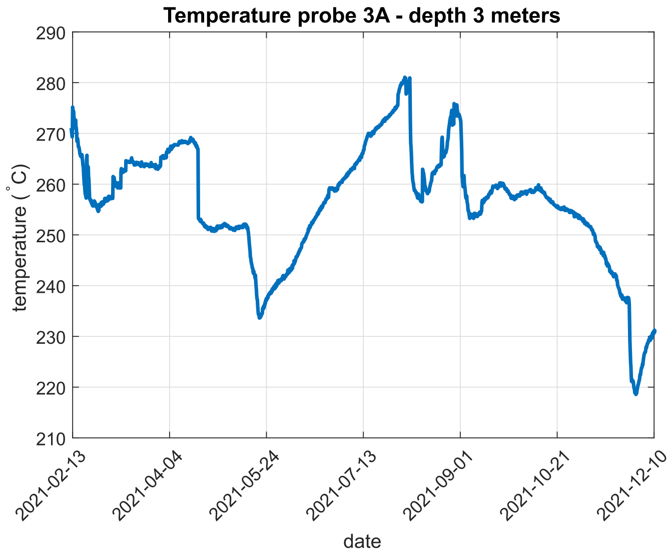

Fig. 14. Course of temperature at a depth of 3 m.

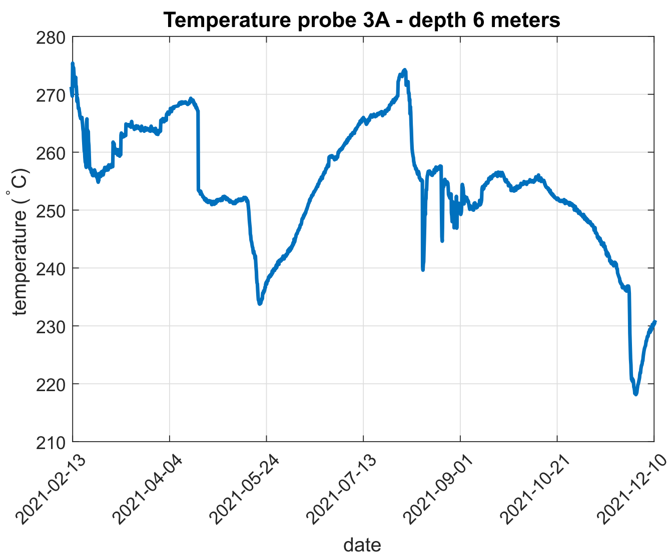

Fig. 15. Course of temperature at a depth of 6 m.

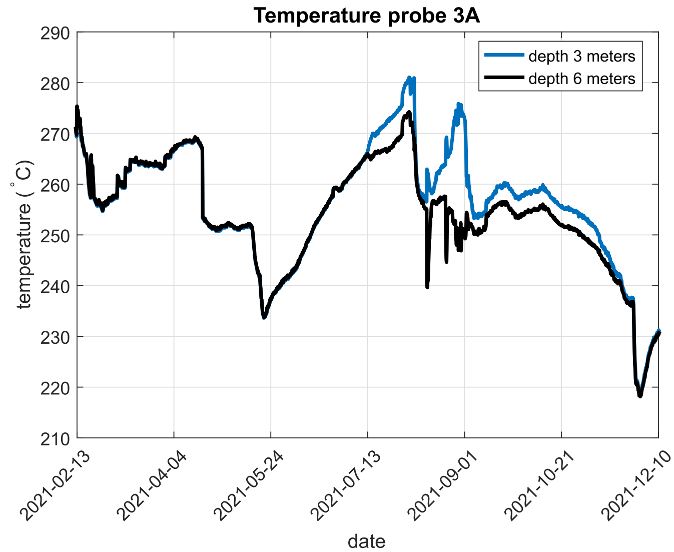

Fig. 16. Comparison of temperatures at depths of 3 and 6 m.

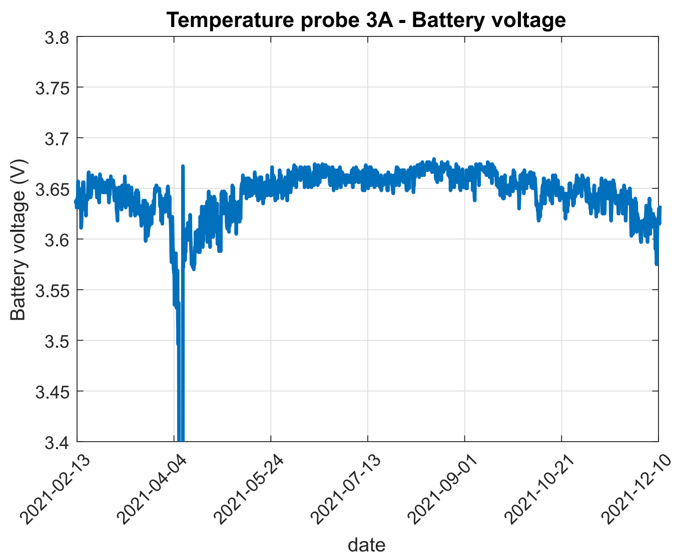

Fig. 17. Course of voltage of the sensor module battery.

When monitoring thermal processes, it is important to monitor the temperature trend for a long time for the sake of prevention. In the event of its sudden increase, it is necessary to start the remediation intervention immediately.

The monitoring systems devised have proven their functionality and have undergone long-term testing in demanding conditions, which are an integral part of mining and landfill waste sites. The components of these systems must be resistant to many external influences. These are mainly humidity, dust, high temperatures, and aggressive fumes of sulfuric acid compounds.

The type of material suitable for the temperature sensor data line is a significant problem that had to be addressed. When monitoring thermal processes in mining dumps, temperatures in the order of hundreds of degrees Celsius commonly occur. Here, conventional data lines made with polyurethane cable or even special cables based on Teflon and silicone are no longer usable. The only option is to use special thermocouple probes, which are located in flexible metal (stainless steel) housings.

Overall, the monitoring systems implemented proved the correctness of their design and their deployment and operation was smooth.

Figs. 14–17 show time courses of the temperatures measured by the 3A probe and power battery voltage for the period from February 13, 2021, to December 10, 2021.

Fig. 14 shows the course of temperature at a depth of 3 m in the 3A probe.

Fig. 15 shows the course of temperature at a depth of 6 m in the 3A probe.

Fig. 16 shows a comparison of temperature curves at depths of 3 and 6 m in probe 3A.

Fig. 17 shows the MATLAB graph illustrating the course of the battery voltage. The graph shows that on April 8, 2021, the battery was replaced.

Fig. 18 shows that the data were captured at a resolution of 32×24 pixels. These raw data are stored to an SD card for later use and evaluation. For real-time transmission and on-site monitoring, it was necessary to reduce these data to a

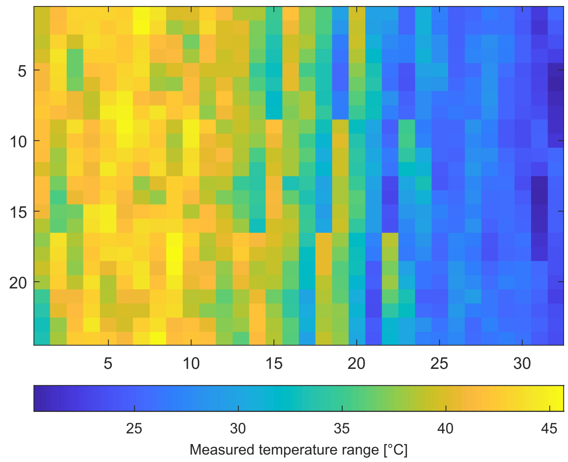

Fig. 18. Example of the nonreduced data measured by the MLX90640 sensor—matrix at a resolution of 32 × 24 pixels.

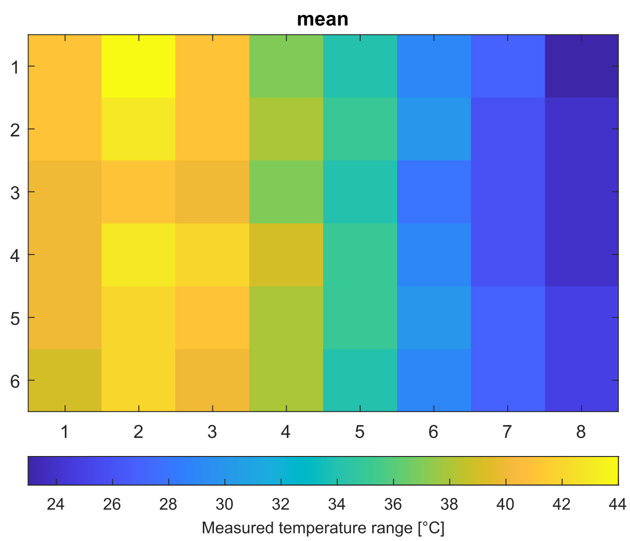

Fig. 19. Example of reduced data, ready to be sent using LoRaWAN—matrix at a resolution of 8 × 6 pixels.

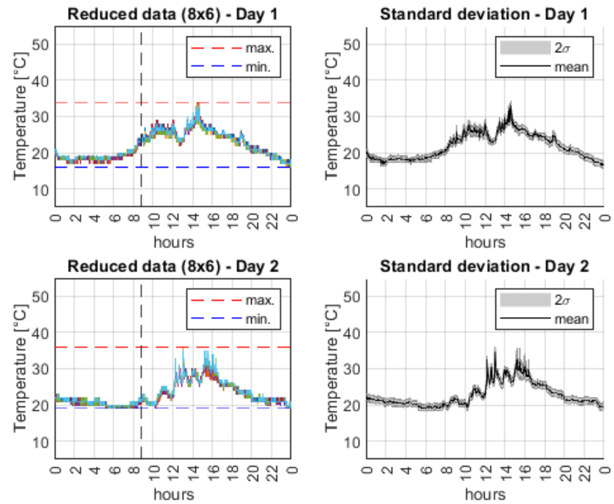

Fig. 20. Measured and reduced data with computed standard deviation.

resolution of 8 × 6 pixels. The size of the resulting matrix is based on the technological limitations of LoRaWAN itself. The reduced data are illustrated in Fig. 19.

Fig. 20 shows the course of continuous measurement over two days and the standard deviation of mean temperature.

V. Discussion

The trend of remote and automated data reading to control the monitoring of environmental processes (or crisis situation prevention) is spreading across ever more industries. When it comes to waste management, smart technologies are used in all the phases: 1) from just collection vessels [31], [32], [33], 2) monitoring of wastewater management [34], [35], and 3) air dust or gas pollution [36], [37] to inspection of landfills. It is, therefore, a long-term trend that will continue to deepen with the increasingly stringent waste management requirements and the support the "Smart City" concept. The graph in Fig. 14 shows the course of temperatures in the measuring probe installed at the Heřmanice mining dump at a depth of 3 m for a period of one year (2021). The curve shows a slight historical trend of decreasing temperature.

Monitoring of temperature processes at the Heřmanice mining dump was started in January 2021. It has been continuously going on in several measuring probes until now (04/2022). The monitoring system described above is installed in one measuring probe, which is installed in the place of the greatest intensity of the thermal process and where the temperatures are in the order of several hundred degrees Celsius. Hence, thermocouple sensors were used. The area of the thermal process was remedied in depth using a grouting mixture to prevent further spread. The efficiency of grouting cannot be relevantly evaluated in such a short period of time; a geotechnical engineer will have to be invited for a detailed analysis. However, a slight drop in temperature is already evident from the course of the graph.

The aforementioned monitoring systems proved their correct operation within their real operation at the selected landfill and mining dump. Their construction is robust and enables implementation in other real places where it is necessary to monitor the temperature or other relevant quantities for a long time. The monitoring systems devised and implemented are unique and modularly configurable. They have considerable advantages over available commercial systems. A complete compact battery-powered autonomous high-temperature measurement system that uses thermocouples was not commercially available at the time of installation. For these reasons, our own comprehensive monitoring system has been developed.

In the future, monitoring systems can also be expanded with the ability to power them with rechargeable batteries that can be charged via photovoltaic panels. Equipping the monitoring system with rechargeable batteries increases the energy capabilities of the monitoring system, and it could be equipped with sensors for monitoring concentrations of dangerous gases such as CO or CH_4, as mentioned in the [15] article. However, as mentioned in Section III, for unguarded areas, equipping the monitoring system with photovoltaic panels increases the risk of theft of monitoring system components.

VI. Conclusion

The article dealt with the issue of prevention of thermal processes and methods of their measurement at mining and landfill waste sites. The team presented two specific monitoring systems for temperature measurement. The advantage of the proposed solutions is that they allow autonomous monitoring of large areas without the need for manual measurement and reading of the values. Relevant data are periodically transmitted wirelessly to the database repository, while the system built in Grafana allows operators at dispatching workplaces to monitor the development of temperatures and other relevant quantities online. The only disadvantage of these systems is that the LoRa and Sigfox IoT technologies used are not standard for the deployment of large sensor networks. Certain operating fees must be paid for each measuring point or probe. It is, therefore, necessary to effectively balance the number of sites monitored and the operating costs of the entire system. However, this problem can be solved using an alternative technology, such as IQRF[1], which allows the implementation of large low-power sensor networks in the MESH topology. In this case, one network coordinator also acting as a communication gateway was able to communicate and obtain data from up to 239 measuring points (nodes). The use of this technology will be the subject of future development of both the measuring systems.

[1]Registered trademark.

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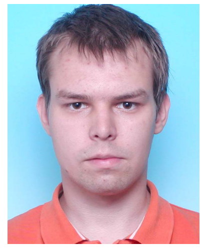

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