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Digital Twin of the Mining Shaft and Hoisting System as an Opportunity to Improve the Management Processes of Shaft Infrastructure Diagnostics and Monitoring

Piotr Kalinowski, Oskar Długosz and Paweł Kamiński

Abstract

The following chapter presents a concept of a virtual model of a mine shaft equipped with a hoisting system for the purpose of improving the processes of diagnostics management of shaft infrastructure and its monitoring. The chapter presents a proposal of improvement of broadly known processes such as: diagnostics and monitoring of shaft infrastructure using digital models of 3D structures, the BIM and Digital Twin idea. Implementation of such systems in the operating mine working was presented together with expected results of monitoring. As the presented solution is currently only a concept, development of such system in real application is necessary to assess real benefits of application of Digital Twin system.

Keywords: mine shaft, data visualization, digital twin, digital model, mine shaft hoisting system, diagnostics, monitoring

1. Introduction

Mine shafts along with hoisting systems are ones of the most important parts of underground mines' technological chain. Their correct work is crucial for mine economy and safety of miners and all of the mine's infrastructure. Mine shafts, especially those equipped with hoists, are necessary for the transport of materials, staff, and excavated material. Mine shafts are the only way of rescue from the mine workings. They are also needed for a proper work of mine ventilation system [1].

Mine shafts infrastructure is under constant influence of destructive forces, both geological and anthropogenic origin, which are caused by number of factors, such as local deposit's tectonics (geological structure), rock mass movements caused by pressure effecting from deposit exploitation, atmospheric conditions, groundwater acting on the shaft lining etc. Law and safety regulations ensure that condition of shaft lining and infrastructure is controlled to provide proper levels of safety and efficiency of the shaft. Reliable periodic inventory and tests are made to prevent shaft lining and equipment from destruction. To ensure shaft's safety, despite

conducted tests, competent analysis of collected data and quick decision making are needed. It is sometimes necessary to take actions, such as cessation of shaft's operation, repair of shaft equipment elements, which are costly, but necessary to prevent further shaft destruction and to ensure safety of the mine, environment and, most important of all, people's lives and health [2].

Incorrect or unreliable monitoring of shaft infrastructure and data analysis or negligence in those processes can lead to tragic consequences. Proof of how important is proper mine shaft control and monitoring, is an incident, which took place on September 4th 2008 in "Szczygłowie" colliery, part of "Kompania Węglowa S.A.", located in Knurów, Silesian voivodeship, Poland. As the result of this incident, shaft top building of shaft V, main ventilators station, former hoist building, head frame and elements of electricity infrastructure were destroyed [3, 4].

Shaft lining's instability caused sinkhole with radius about 30 metres. Around the sinkhole a danger zone with radius about 100 metres were created. The incident caused abnormalities of functioning of ventilation system both "Szczygłowie" colliery and adjacent "Knurów" mine. In the effect of this, concentration of gases in workings exceeded limits, which was a reason of evacuation of 433 employees of "Szczygłowie" and 92 workers of "Knurów" mine (509 people total). There were no fatalities [5].

Photos below (**Figure 1**) presents sinkhole and remains of the shaft V.

Despite of the rapid character of buildings collapse and sinkhole propagation, the incident was foreseeable. Tests conducted in the shaft V remains showed faults of the shaft lining, which led to the incident. However, incidents which are impossible or almost impossible to foreseen also happen in mines. For example, in R-II shaft of "Rudna" copper mine, part of KGHM Polska Miedź S.A., shaft of the hoisting machine was partially broken in 2011. It resulted in temporal suspension of the mining shaft operation, which brought huge financial loss for the whole company, because hoisting system operating in R-II shaft was one of the most important elements of technological chain not only of the "Rudna" main, but also for the whole KGHM [7].

Photos below (**Figure 2**) presents fracture of the hoist's shaft.



Figure 1.
Sinkhole and remains of shaft V, Szczygłowie colliery [6].



Figure 2.
Fracture of hoist's shaft [8].

Many different incidents happened in the long history of mining. One of their numerous reasons is lack of proper mine shafts control, caused either because of the lack of possibilities of conducting one or negligence in monitoring.

2. Control and revision of shaft infrastructure

As it was said before, technical condition of mine shafts' lining and equipment is a foundation for safe underground mine operation. **Figure 3** presents influence of the main workings technical condition on safety of the whole underground mine and its vicinity.

As it was indicated in the introduction, application of Digital Twin system will improve the safety of the whole underground mine. Mine shafts are crucial for maintaining proper mine ventilation and providing transport of people, materials and excavated material. In case of danger, they are the way of staff evacuation, which is essential for people's safety.

It is obvious that condition of particular shaft elements, like hoisting machine, shaft lining or shaft members is reflected in the safety of mine shaft operation. Inappropriate operation of some of these elements can lead to a stoppage of shaft operation, which affects mine's economic performance. In extreme situations, such as those presented in introduction, economic performance of the mine is in a serious danger, because of high cost of claiming the settlement. What is even more

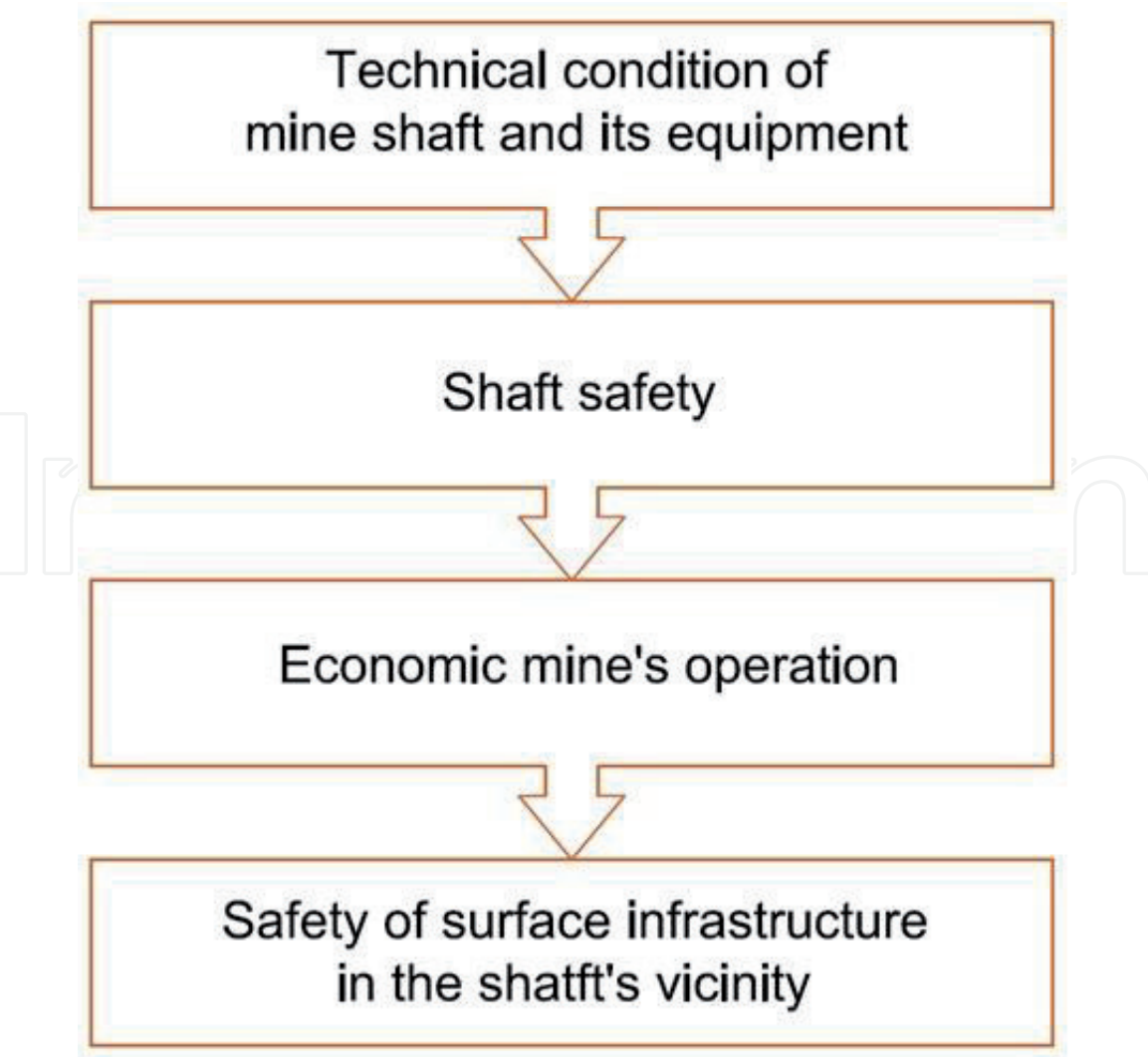


Figure 3.
Influence of technical condition of shaft infrastructure on underground mine's safety.

important, such situations can cause serious threat for staff of the mine, as well as for bystanders, as mine shafts are sometimes located in the urbanized area.

Instability of shaft's lining can be caused by:

- static load and change in conditions of cooperation of lining and rock mass,
- groundwater flow through the lining,
- deformational load of rock mass,
- dynamic rock tremors,
- utility factors and technological defects,
- aging of lining's material.

Shaft lining damage can lead to serious failures or even disastrous consequences, such as those described in the introduction.

Effects of the shafts' failures can be as follows:

- hazard for employees' lives or health,
- malfunction of ventilation system,
- water, methane or fire hazard,
- shaft failure causing impossibility of its operation,
- damage of buildings located on the surface,
- necessity of temporary suspension of mine operation [1].

According to Polish law regulations mine shafts and their hoisting systems are considered main (literally called "basic") elements of underground mine. Hoisting system with its whole equipment has to be maintained and controlled in a very strict manner, presented in regulations. Use of malfunctioning or broken hoisting system is strictly forbidden by the law [9].

Particular regulations require specific periods of time between specialized inventories of numerous shaft elements by different responsible people. These people are in particular different mine supervisors as well as appraisers.

2.1 Disadvantages of currently used systems

Mine shaft is an underground mine's bottleneck, which efficiency is in a relationship with mine's economic performance. Thus, it is desired to take all of the actions to prevent interference of the shaft elements control with its regular operation, as well as its temporal suspensions caused by potential failures or not scheduled maintenance works.

Methods of shaft monitoring are also considered not enough effective nor precise. To solve this problem, idea was presented to, utilizing modern technologies, visualize mine shaft data using specialized measuring methods and software. This way of data collecting, presenting and analysis can have positive impact on mine shaft levels of safety and effectiveness, by reducing time of non-operative work time of the hoisting system [10, 11].

3. Data visualization – the idea of digital twin of the mine shaft

During analysis of current state of art of mining, automatic and information technology, idea of mine shaft's digital twin construction was born. Mine shaft equipment, with numerous monitoring devices, which data can be collected, analyzed and processed in real life, can effect in more reliable and accurate forecasts of failures or stoppages of shaft operation. The key factor of this idea's success is integrity of applied solution. To provide full and complex data, it is needed to cover different elements of shaft elements monitoring. The most important of them is visual examination (using video cameras). The other aspects to analyze are power consumption, temperature of particular hoisting system elements, season, head frame deflection, etc. [12, 13].

The main problem to be solved is to state relationships between many, seemingly unrelated, factors. Future goal is to make the digital twin independent structure with decision making mechanism, to decide about the parameters of needed maintenance works or necessary stoppages. To achieve this goal, it is essential to spend time to “teach” the machine how to make appropriate and safe decisions, compliant with law regulations and experience of mine management and engineers. Having knowledge and experience, the machine should analyze collected data and their influence on other factors, as well as compare their quantities with limit values [14].

4. Devices for data visualization

4.1 Digital engineering solutions

Technologies developed by DES are engineering tools utilizing artificial intelligence for ACE market (architecture, construction and engineering) and asset management. DES' solutions are also present on NDT market (non-destructive testing), as well as BIM and EAM.

Software developed by *Digital Engineering Solution* utilizes pictures and files taken by drone, phone or camera. Advanced algorithms provide image processing, which allows to observe changes on monitored objects, such as size and location of fracture (**Figure 4**), elements displacement, deflection etc. Collected data can be stored and evaluated to assess risk and reliability of analyzed solutions [15].

Characteristic features of DES solution are:

- utilizing smartphones as measurement devices,
- processing of photos and videos for infrastructure monitoring and damage detection (using artificial intelligence),

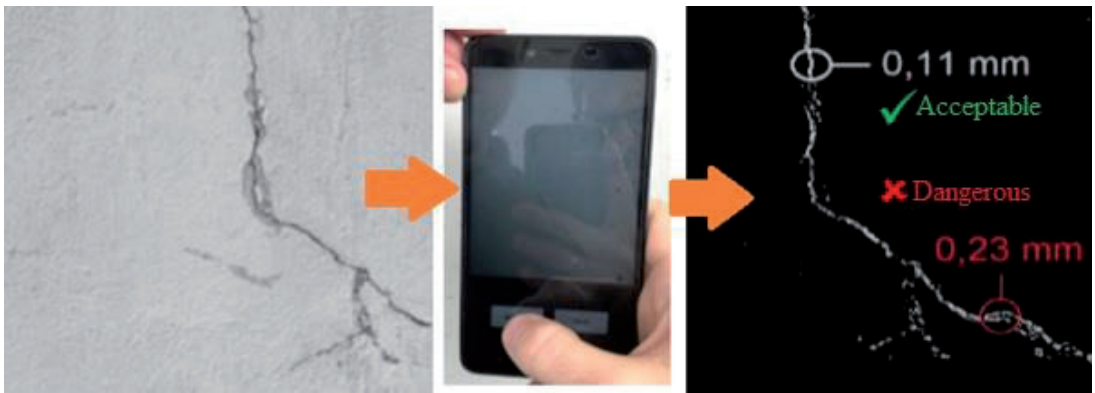


Figure 4.
Example of DES measurement application [15].

- drafting 3D BIM models from photos (taken with smartphone or any other device, such as intrinsically-safe camera ATUT), as well as their updating with current test data (to assist in decision making process).

Use of DES platform allows to decrease time needed for monitoring process initiation from days to minutes. DES innovative solution is an answer for global need for low-cost monitoring systems. In terms of pandemic crisis and quick technological advance it is a real issue [15].

4.2 ATUT, intrinsically-safe system

Specific environment of the monitored object force usage of devices with particular features and complying certain safety standards. Such solutions, which meet mining industry safety standards are produced by Polish company PPHU ATUT sp. z o.o., so they can be used to extend potential of digital twin.

AT VIDEO system is used to obtain video footage from hard-to-reach places, as well as from areas which are particularly dangerous, in which attendance of people should be restricted. ATUT system support multiple video cameras at the same time and data transmission of digital image in mine workings and on the surface, using fiber-optic Ethernet network. Such solution enables reduction of fibers number.

ATUT, intrinsically-safe video system consists of:

- AT-NODE/G – node of redundant fiber-optic backbone,
- PZW-1/ATVisio-2 – surface visualization unit using ATVisio-2 software,
- ISE-1 – intrinsically-safe Ethernet network switch,
- KM-2 – media converter,
- DZW-1 – underground fireproof computer,
- IKA-1 – intrinsically-safe video camera.

IKA-1 video camera is a standard system element. This camera is equipped with automatic aperture control, regulating light intensity. In case of extremely-low illumination the camera sets itself in the black and white mode. Recorded image is transferred by fiber-optic network or coaxial cable with tele-technical twisted pair. If utilization of fiber-optic installation is impossible, fiber-optic video converter might be used [16].

Diagram of the system's idea is shown in **Figure 5**.

There are also other solutions utilizing data visualization available on the market, such as:

- ATUT-RFID – system that allows assessment of type and mass of materials transported with the hoist influence on correctness of hoisting system work,
- AT-Location – system used to localize mine workers both in underground workings and on the surface (as well as during transportation in man shaft). Data is collected in near-real-time and saved [17].

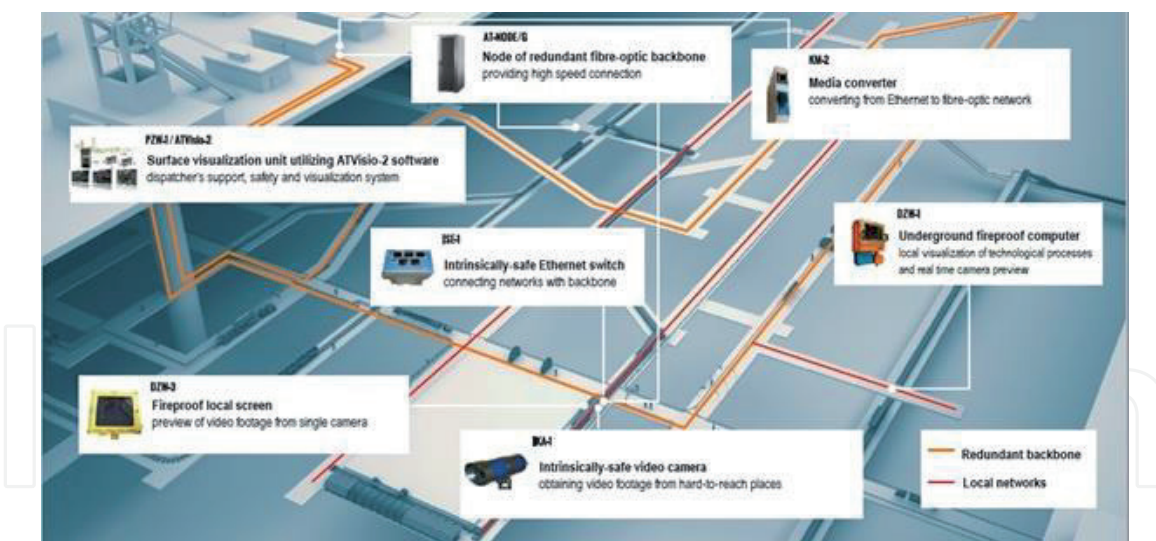


Figure 5.
 Idea of AT-VIDEO system application in an underground mine [16].

4.3 3D scanning

In the last few years one can see rapid development of laser scanning technology. Numerous researches and tests are carried out on its use for inventories. *Skala 3D* company introduced mobile system for automatic mine shafts geometry measurement, which provides full and precisely mapped model of the object. It is based on data collected by laser scanners and inertial unit. Use of GPS is impossible for measurements carried out with the system, because tests are conducted underground. Thus, trajectory of scanners' motion is determined by geometrical data, accelerometers and gyroscopes of inertia unit. System is also equipped with set of vibroisolators, to prevent influence of platform's vibrations during its movement in the shaft [18, 19].

The whole system presented above is a fully calibrated measurement unit, which can provide spatial data from measurements of analyzed shaft in relatively short time. Accuracy of measurement is about 2–3 mm in one measurement plane. The system is considered accurate enough for in situ tests in mine shafts [19].

4.4 GPS measurements

In specialized literature one can find multiple examples of use of GPS measurements undertaken for civil engineering and also for mining engineering. One of them is its use for Polish coal mine LW Bogdanka, where in year 2012, system of head frames tops displacements monitoring, applied by Department of Geomechanics, Civil Engineering and Geotechnics of AGH UST in Krakow. Final effects were satisfactory. Broad range of GPS use possibilities as well as positive research experience indicates that this technology might be very useful for similar purposes [20]. **Figure 6** presents head frames of Bogdanka's shafts with GPS antennas mounted on their tops.

4.5 Other devices

To provide full control of mine shaft infrastructure numerous other devices can be used. Examples of such devices are thermal imaging cameras installed on different elements of shafts or hoisting systems to monitor temperature of breaks,



Figure 6.
Head frame of S1.2 shaft, LW Bogdanka coaliery.

hoist shaft, etc. Such applications might be useful for control of hoisting system performance. Thermal cameras systems for mine shaft's applications must be intrinsically safe and have wide measuring range, to provide safe work during all phases of shaft's operation, including its sinking (with utilization of rock mass freezing).

4.6 Geotechnical monitoring of rock mass and mine shaft lining

Proper shaft lining monitoring is crucial to provide safe shaft operation. It is required by Polish law on every phase of shaft existence – its sinking, operation and liquidation. Tests cover several parameters of shaft elements and equipment, such as:

- condition of shaft lining, defined by observations, destructive and non-destructive tests,
- shaft's lining integrity,
- lining's stability,
- correctness of shaft members installation,
- shaft elements' state of wear [21].

Shaft lining monitoring can be carried out by:

- *Vibrating Wire Stressmeter GEOKON,*
- *NATM Shotcrete Stress Cell Geokon,*
- *Concrete Stressmeter Geokon,*
- *Smartec SOFO Standard Deformation Sensor,*
- *NSM/ENSM system by Elexon Mining.*

One of the most important factors of proper mine shaft's monitoring is arrangement of measurement devices. Such theoretical devices arrangement is shown in **Figure 7**.

4.7 Idea of monitoring system

Complex graph of idea of monitoring system is presented in **Figure 8**.

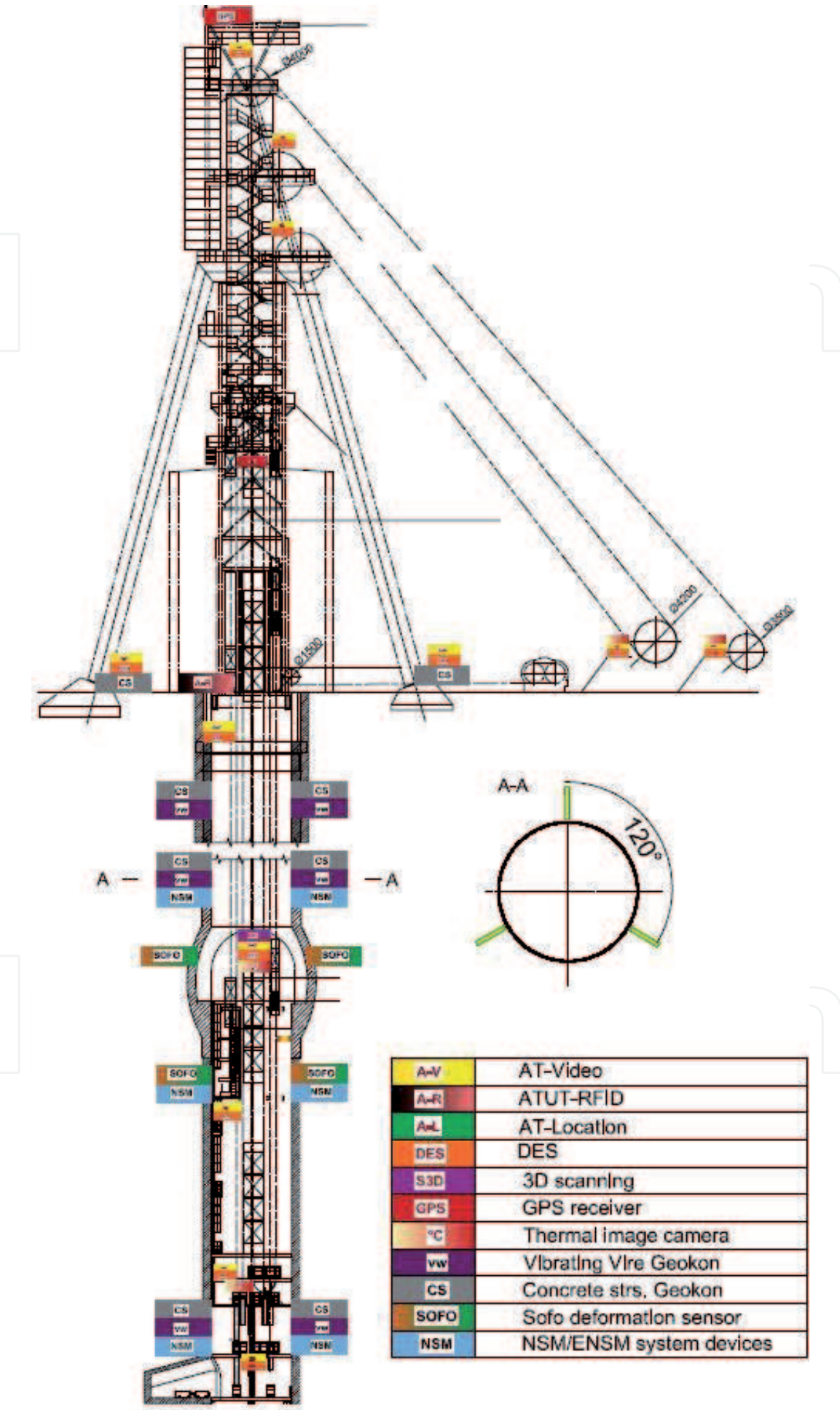


Figure 7.
Example of devices' arrangement for mine shaft monitoring.

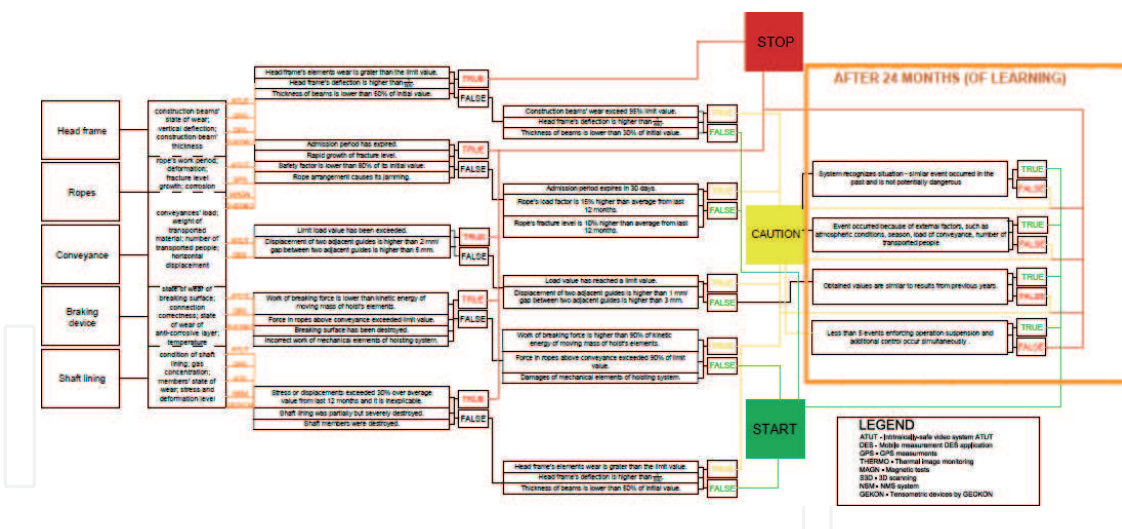


Figure 8.
Idea shaft lining and hoist monitoring system.

4.8 Management of diagnostics

To provide effective operation of a shaft and its infrastructure, proper planning of all suspensions, maintenance works, revisions, controls and inventories is needed. Digital twin of mine shaft might be useful for that purpose. However, to ensure complete diagnostics management it is worth employing models and applications used in civil engineering. Their utilization in mine shaft monitoring should significantly improve safety and economic performance of the mine. Application proposed for diagnostics management of the shaft infrastructure as well as the whole mine are presented below.

BIM (Building Information Modeling) – is a process supported by various tools, technologies and contracts involving the generation and management of physical and functional characteristics of places. Parametrical data is gathered to provide information about analyzed infrastructure. BIM is a tool for generating building data, its designing and management during operation. BIM's characteristic feature is easy access to data, so all stakeholders can have access to the same complete information. Parametric data record ensures possibility of computer modeling of building (basing on tables, calculations, data analysis, etc.). Use of BIM goes beyond the planning and design phase of project, extending throughout the building life cycle. The supporting processes of building lifecycle management includes cost management, construction management, project management, facility operation and application in green building. The most popular BIM software are programs Autodesk Revit and Graphisoft Archicad.

BIM models are visually attractive but not automatically updated, so they do not contain current data about state of the infrastructure or its damages. Thus, it is recommended to extend BIM models using other technologies. Digital data of BIM model is often supported using additional applications. Some of these applications are presented below.

4.9 Mobile applications in civil engineering

Doxcel utilizes software based on artificial intelligence for image analysis to give real-life information about timeliness of scheduled operations, budget implementation or even quality of work at construction site.

Building System Planning is a solution based on automation of civil engineering project planning. One of its elements is GenMEP, software used for automation of

mechanics, electric and hydraulic installation design, in terms of BIM. For example, GenMEP can automatically and autonomously design different installations for building of which its 3D model was previously made. Purpose of use of such software is to prevent colliding several installation elements in one place.

Autodesk BIM 360 DOSC is an application for management of documents on construction site, which is also adapted for teamwork. There are also similar software solutions available on market, e.g., PLANGRID and PROCORE. Usually they provide photo documentation management, but without advanced image analysis. Their most important features are reporting, time and budget management. They also support management of contacts, meetings, deliveries, etc. There are also other applications for individual clients, such as mobiDOM, which consist of schedule, organizer, contact database, etc.).

Digital Engineering Solutions in cooperation with Przedsiębiorstwo Budowy Szybów S.A. (Shaft Sinking Company, part of JSW Group) developed an application

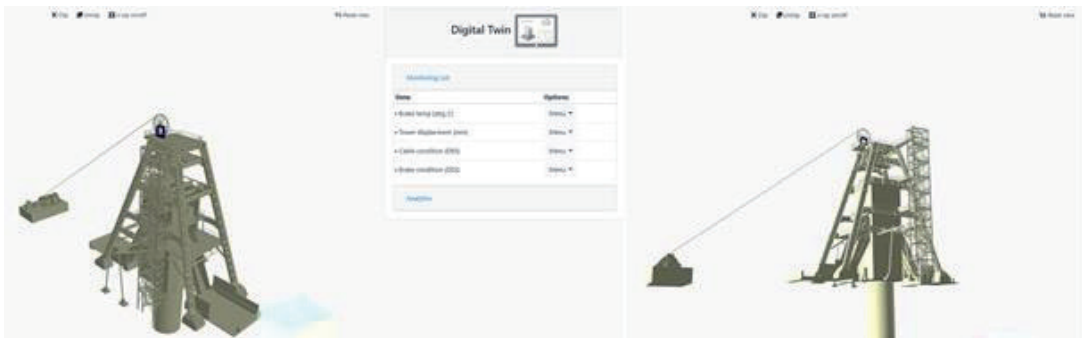


Figure 9.
Model of mine shaft and hoisting system made with DES's application.

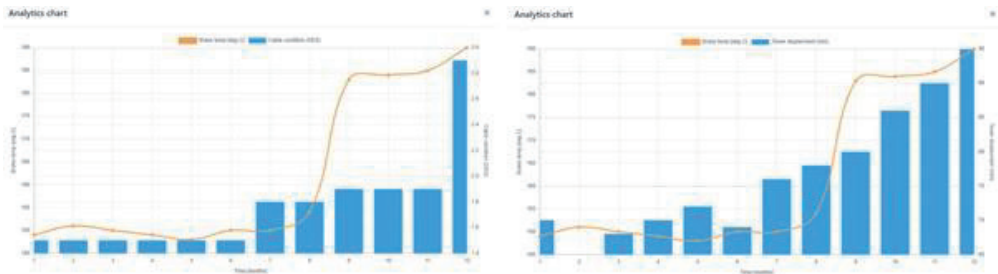


Figure 10.
Graphs of shaft elements' data and relationships between them.

Analytics table

Loading, please wait

Time	[months]	1	2	3	4	5	6	7	8	9	10	11
Brake temp [deg C]	oC	149	151	150	149	148	150	150	154	183	184	185
Tower displacment (mm)	mm	70	65	68	70	72	69	76	78	80	86	90
Cable condition (DES)	-	1.5	1.5	1.5	1.5	1.5	1.5	1.8	1.8	1.9	1.9	1.9
Brake condition (DES)	-	1	1	1	1	1	1	1	1	2	2	2

Run simulation Close

Figure 11.
Table of shaft element's data.

prototype for digital twin development. The concept and real-life application possibilities are currently an objective of further development. Picture above (**Figure 9**) presents an example of a model made with this application.

Presented application enables user to present data in graphical form, as well as show relationships between them. **Figure 10** presents graphs and relationships of brake temperature and rope condition (on the left side) and break temperature and tower displacements (on the right-hand side). In the **Figure 11** table made with DES's app and presenting data listed above is shown. Orange and red color indicates dangerous states.

5. Discussion

Table 1 below presents simplified SWOT analysis of proposed solution of Digital Twin. Obvious advantages of such system are improvement of safety in the mine workings in which monitoring is to be used. Improvement of economic performance of the mine is possible only if investment costs and spending on training or hiring qualified staff are not too high. However, it is very hard to assess real saving achieved by application of Digital Twin. It might be real issue, because saving in case of situations similar to those presented in introduction might be huge, but in other cases they can be as well unnoticeable.

Idea of Digital Twinning is a pioneering solution in Polish mining industry. The coal-based industry suffers from underinvestment, which leads to a situation in which the whole industry is out-of-date. As the CO₂ emission allowances' prices are constantly raising, it might be hard to introduce such system in a dying industry. A chance for development of Digital Twin system is an industry of raw materials, such as copper etc., because demand for such resource is constantly growing.

Strengths	Weaknesses
<ul style="list-style-type: none">• improvement of the safety in the mine shaft and its vicinity,• improvement of mine's economic performance,• increase of the automation level of the mine	<ul style="list-style-type: none">• high investment cost,• demand for qualified staff,• problematic installation in operating shaft
Opportunities	Threats
<ul style="list-style-type: none">• possibility of detailed analysis of gathered data,• possibility of conducting research basing on archived data,• possible development of the system, covering other mine objects or different branches of industry,• potential financial profit	<ul style="list-style-type: none">• a conflict with some regulations (necessity of adjustment of law regulations),• necessity of employment or training highly qualified staff

Table 1.
Simplified SWOT analysis of digital twinning.

6. Conclusion

In the chapter, idea of comprehensive monitoring system of mine shaft infrastructure, as well as tools supporting diagnostics management were introduced. Presented solution utilizes modern technologies, including BIM and Industrial Internet of Things. Main goal of digital twin of mine shaft is reduction of unscheduled suspensions of shaft operations and improvement of its safety, by constant shaft elements monitoring with analysis of gathered data. Mutual influence of

different shaft elements and their impact on reliability of its operation can be also done basing on data collected during control process. In long time period it might reduce costs of shaft maintenance.

Theoretical model of mine shaft monitoring was prepared according to existing Polish law. Goal of this venture is to prepare comprehensive visualization of mine shaft and its equipment, to provide virtual analysis of its behavior. Monitoring system should be able to learn how to react for different events occurring in shaft elements, using systems such as ABB Ability™ or similar (SYSTEM PI) and proper monitoring unit. Decisions made by software might be displayed on responsible person's computer screen. Systems such as DES consists of digitization both underground and surface infrastructure. In future it can provide assessment of mining damage, using scanning, modeling, EAM integration and, as an effect, introduction of BIM and EAM mechanisms. Such solutions might help reducing amount of money spent by mining companies to handle mining damage, which is real issue, because in 2018 only JSW Spent 92 million zł (approximately 25 million USD) for this. Presented idea is a only a theoretical solution, so it's real life applications needs further analysis to determine amount of measuring devices, their location and performance in hard conditions of mine shaft. Digital model of mine shaft and hoisting system has a positive impact on economical effectiveness of mine and shaft itself, as well as safety of mine staff and infrastructure. On the side of disadvantages there are high investment cost, long time of system introduction and its "learning" and reliability of applied devices and systems. However, in long time perspective costs presented above are much lower than losses resulting from unscheduled suspensions of shaft operation. Improvement of people's safety is also very important result of digital twin application.

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