Digital Twin Technology in Data Center Simulations

Subjects: Mining & Mineral Processing

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Mining activities often deem mine sites as temporary, leading to their eventual reclamation, rehabilitation, or abandonment. The abandoned mine sites can be reimagined as strategic assets, thus providing economic benefits while adhering to critical data center infrastructure standards.

data center transformation mine site re-purposing environmental simulation sustainable reclamation ventilation optimization smart mining

1. Introduction

Traditionally, mining is viewed as a temporary land use, the value of mine sites being temporary and primarily tied to the extraction phase. Upon resource depletion or the cessation of economic viability, these sites are often abandoned. The neglect of proper rehabilitation strategies for these sites poses significant environmental risks, such as acid mine drainage (AMD) and contamination from tailings and waste piles [1]. Estimates indicate a significant number of such neglected sites, with figures suggesting around 10,000 in Canada and 5500 in Japan [2]. Recent years have witnessed increased engagement from academic and financial institutions in crafting frameworks for responsible mine closure [3]. Current regulations necessitate the integration of closure and reclamation plans within mining operations, targeting the restoration of landscapes and the mitigation of environmental and socio-economic impacts [4]. While essential, rehabilitation and restoration efforts categorize mine sites as transient land uses, generating no continual revenue but incurring restoration costs. This issue is particularly salient for vast, abandoned underground mines, where complete restoration is often impractical. Re-purposing these underground spaces provides an opportunity for sustained land use, potentially fostering industries capable of supporting the sites’ maintenance and rehabilitation costs [5].

Underground sites offer distinct advantages: they exhibit greater resilience to earthquakes and extreme weather and maintain consistent internal conditions, unaffected by external climate variations [6]. These sites often feature existing infrastructure—like power lines, transport pathways, and ventilation systems—which can be leveraged in re-purposing efforts. However, re-purposing requires continuous monitoring of safety parameters, including communication systems, air quality, and geological stability. Accessibility to these sites is often limited due to their remote locations and depth-related safety challenges. The sites’ distances from communities can further complicate re-purposing efforts [6]. Given the access and maintenance challenges of underground spaces, autonomous systems that minimize human intervention are preferred. Implementing a digital twin of the target site enables the use of simulation tools for designing, operating, and monitoring the underground space remotely. This integration not only streamlines operations but also facilitates informed decisions through real-time data, creating a synergistic cyber-physical system (CPS) [5].

2. Smart Mining

The evolution of digital technologies has paved the way for a new era in mining, known as “smart mining”. Smart mining refers to the integrated approach to optimizing mine operations and improving productivity, safety, and environmental impact through real-time data analysis, automation, and advanced technologies [7][8]. One crucial aspect of smart mining is the real-time monitoring and operational control enabled by the internet of things (IoT) and other connected technologies. Ikeda et al.’s (2021) exploration of sensor data communication in underground mining environments highlights the significance of robust and efficient data transmission systems. Their research compares and optimizes multiple installation sequences, contributing to the improvement of real-time data relay and decision-making processes underground [9]. In addition to real-time data monitoring, smart mining also embraces innovative solutions for operational challenges. The work by Ikeda et al. (2019) underscores this aspect through the development of an underground in situ stress monitoring system using multi-sensor cells and Wi-Fi direct technology [10]. This system not only enhances mining safety by providing immediate stress measurements but also improves operational efficiency. The integration of artificial intelligence (AI) and machine learning (ML) in smart mining operations has further transformed traditional practices. Deep learning techniques, for instance, are being utilized for estimating muckpile fragmentation. Ikeda et al. (2023) employed simulated 3D point cloud data for this purpose, demonstrating the potential of this technology in enhancing ore recovery and reducing waste [8].

Smart mining, therefore, represents a multifaceted approach to modernizing mine operations. By leveraging digital technologies, mining companies can significantly improve operational efficiency, ensure the safety of mine workers, and minimize environmental impact. As this field continues to evolve, further advancements in IoT, AI, and automation are expected to drive the future of mining toward unprecedented levels of optimization and sustainability.

3. Digital Twin

A digital twin represents a real-time digital counterpart of a physical entity, process, or service. Unlike a prototype, a digital twin autonomously synchronizes data between the physical and digital models, reflecting any changes occurring in the physical model in the digital one. This synchronization is possible through the integration of various digital technologies, including but not limited to, the internet of things (IoT), cloud computing, analytics, and artificial intelligence (AI)—components of Industry 4.0. A digital twin comprises a physical object, its digital model, sensor-acquired time-series data, and the connections between them [7][8][11]. **Figure 1** illustrates the structure of a digital twin within a cyber-physical system.

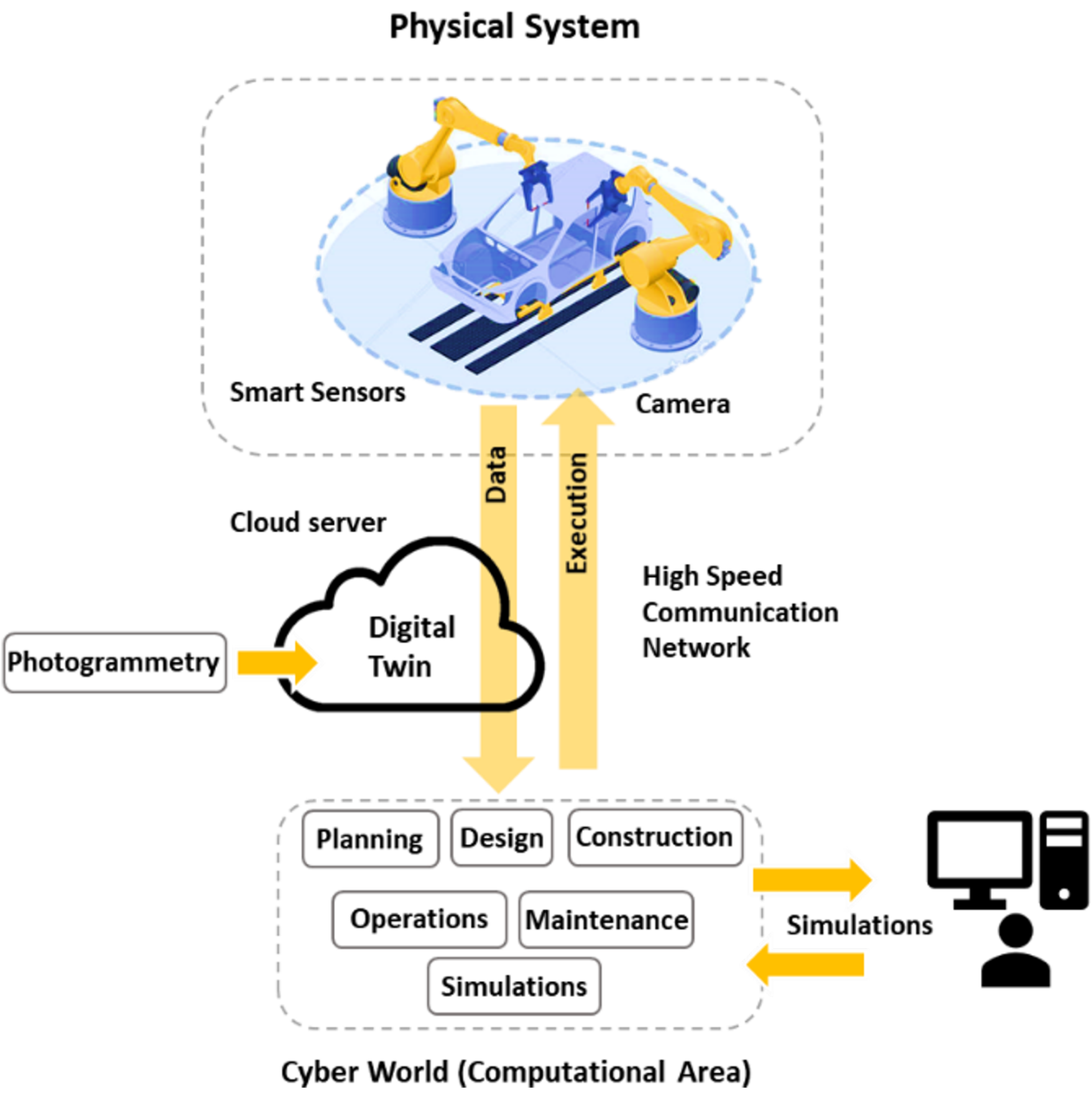

Figure 1. Structure of a digital twin.

Data-driven decision making is enhanced by integrating simulation programs with the digital twin, linking physical systems to their digital counterparts. This integration creates a closed-loop known as a digital thread, autonomously updating the virtual model with data from sensors in the physical object. The data informs simulations essential for planning, design, and operations, enabling real-time, informed decision making and risk assessments. Moreover, integrating simulations facilitates the prediction of various outcomes, enhancing operational strategies.

The benefits of utilizing a digital twin include:

- Real-time monitoring and control: With IoT, users can access the digital model of a physical entity or process from virtually anywhere.

- Enhanced safety and efficiency: Automated monitoring of remote or inaccessible areas.
- Predictive maintenance and scheduling: AI-driven solutions detect potential system faults, enabling pre-emptive maintenance and avoiding economic losses or safety hazards.
- Scenario and risk assessment: Simulations with varied input parameters allow the prediction and pre-emptive addressing of unforeseen scenarios.
- Improved documentation: Immediate access to real-time information enhances transparency for stakeholders.
- Streamlined operations: Data-driven decision making, bolstered by advanced analytics and interconnected intelligence networks, fosters synergies and collaborative efforts, boosting productivity.

4. Ventilation Simulation Programs

Ventilation control is crucial in underground environments, playing a significant role in the operational profitability of underground mining. The planning and optimization of underground ventilation systems demand rigorous analysis, as minor modifications can profoundly impact the entire system. This necessitates the exploration of various options and scenarios, entailing countless predictions related to the ventilation network, system design, and performance. Such complex predictions are unfeasible without the aid of precise and adaptable simulation tools capable of swiftly assessing multiple scenarios [12]. Ventilation simulation programs facilitate the calculation and assessment of environmental variables—such as airflow, temperature, fog, and relative humidity—based on specified parameters like initial temperature, thermal output, and existing ventilation equipment [13].

Previous studies, including those by Webber et al. [13] and Sasmito et al. [14], underscore the necessity of integrating ventilation simulation software for underground mine site monitoring, highlighting the critical role of simulations in enhancing underground systems. For instance, Sasmito et al. [14] demonstrated the efficacy of simulation models in assessing thermal management’s impact within mines, focusing on the computational analysis of various thermal factors on underground tunnel airflow. Managing thermal conditions in underground environments is intricate, given the need to consider elements like geothermal gradients and internal heat loads from personnel, lighting, and equipment [14].

5. Integrating Simulation Programs with Digital Twins

A well-calibrated digital twin of an underground environment mirrors the actual operational parameters of underground ventilation, incorporating real-time data from sensors within the specified area to offer an updated model of the subterranean conditions. This advanced approach significantly enhances the optimization processes of the ventilation systems. Previous studies have delved into the application of simulation programs for constructing digital twins, albeit in different contexts. For instance, Dahmen et al. [15] explored this concept not for underground ventilation but for space missions, concentrating on the methodology behind digital twin development and its subsequent utilization for experimentation [13].

Mine ventilation simulation software uniquely presents real-time data gathered from sensors deployed in underground mining locations. This real-time feature not only facilitates continuous monitoring but also autonomously updates the digital twin with fresh data from the mine, a capability explored by Sishi et al. [16]. Similarly, Cheskidov et al. [17] discussed the employment of monitoring systems to display real-time data regarding mining engineering structures, with in situ data analysis programs pinpointing inaccurately measured or calculated characteristics, such as slope safety factors or load-bearing capacities, within a nature-and-technology system. These programs then prompt further necessary measurements and computations. Both the study by Sishi [16] and that by Cheskidov [17] examined the use of digital twins' as real-time monitoring platforms capable of immediate problem identification, yet neither delved into their application as simulation tools.

Jacobs [18] offers an extensive review of the research conducted in this domain, identifying gaps, particularly in enhancing the methodology for digital twin development and its application as a simulation instrument for system evaluation (**Table 1**).

Table 1. Different studies discussing integration of digital twin and simulation programs [5].

Source	Development of Digital Twin	Digital Twin Used to Evaluate a System	Digital Twin Used as a Simulation Tool
[19][20][21][22]	F	F	F
[12][14][23][24][25][26]	F	F	T
[15][27][28][29][30][31][32]	T	F	T
[13][33][34][35][36]	T	F	T
[16][17]	F	T	F

6. Re-Purposing of Underground Spaces

The re-purposing of a mine site incorporates elements of the existing mining infrastructure and reconfigured landscape aspects for alternative activities post-closure. Such activity not only aids in transitioning the local economy but also mitigates the mine's loss by fostering new forms of attachment to the site and region [6]. An advantage of utilizing underground spaces lies in their stability. The conditions inside underground excavations remain unaffected by external weather conditions and are nearly constant, simplifying temperature and humidity control. Comfortable subsurface temperatures eliminate the necessity for additional insulation, thus conserving energy and reducing costs. Furthermore, underground structures sustain less damage compared to surface structures under earthquake loading [5] and possess increased resistance to hurricanes, tornadoes, and most weapon system penetrations.

However, obstacles exist in re-purposing mine sites, including their susceptibility to flooding and the requirement for diverse skill sets. The location also poses a challenge, as mine sites are often situated in remote areas, far from communities and towns, leading to minimal community involvement that could otherwise motivate re-purposing. The stability and utility of these spaces must be continually re-evaluated and maintained throughout the re-purposing process to ensure safety. The geothermal gradient may cause temperatures inside the mined cavity to increase with depth, necessitating the utilization of pre-existing mine cooling systems for deep mine sites. Globally, examples of re-purposing are few compared to the number of closed mines. Out of the 1804 inactive mine sites documented in the S&P database, only approximately 141 operations have undergone some form of re-purposing [6].

It is common for a mine site to serve multiple purposes after mining; post-mining transitions frequently encompass various categories of land use. Factors such as proximity to communities, infrastructure connectivity, and company policies also influence the re-purposing of mined underground spaces. The most prevalent re-purposing activities include wildlife habitats, historical museums or exhibitions, cultural or historical precincts, and parks or open green spaces [6]. **Table 2** illustrates other instances of mine re-purposing, like healthcare facilities such as Solotvyno's Allergological Hospital in Ukraine, which specializes in treating patients with respiratory ailments. **Figure 2** depicts underground agriculture employing LED lights and hydroponic technology, while **Figure 3** and **Figure 4** present examples of a former salt mine in Germany, re-purposed for radioactive waste storage, and a former limestone mine, converted into a recreation center, respectively. With technological advancements and enduring demand for metals and other resources, the depth of underground mining sites is anticipated to increase. Re-purposing deeper mines will require considering the geothermal gradient—whereby underground mine temperatures rise with depth—and leveraging previous mine site cooling systems to maintain optimal temperatures.

Figure 2. Blast design at target site.

Figure 3. Drums with concrete shielding to reduce radiation exposure stored in Asse II, previously Asse salt mine. Adapted from [34].

Figure 4. Former limestone mine in Louisville, Kentucky, restructured to create underground bike track. Adapted from [35].

Table 2. Examples of mine re-purposing.

Function	Details	Depth	Mine Name
Underground laboratory	Stawell underground physics lab Kamioka underground laboratory (Japan, 1982)	−700 m −1000 m	Stawell Victoria gold mine Kamioka Mozumi arsenic mine
Waste disposal	Asse II mine (Germany, 1967)	−750 m	Asse salt mine
Geothermal exploration	Underground hot water circulatory system	−2000 m	Hot spring coal slope mine Tangshan coal mine
Industrial tourism	(Canada, 1980s)	−410 m	

Function	Details	Depth	Mine Name
Healthcare	Kailuan national mine park (China, 2008) Solotvyno’s Allergological Hospital (Ukraine, 1965)	−300 m	Solotvyno’s salt mine
Leisure and community	Louisville Mega Cavern—underground bike park (USA)	−30 m	Mega cavern former limestone mine

7. Data Centers

Data centers serve as pivotal infrastructure where organizations house critical applications and data. The paradigm has transitioned from traditional on-premises servers to sophisticated virtual networks, facilitating operations in multi-cloud environments [37]. These centers underpin a myriad of applications and activities, encompassing virtual desktops, enterprise resource planning, and advanced realms like artificial intelligence and big data analytics. **Figure 5** illustrates the basic components in a data center facility, highlighting their complex architecture.

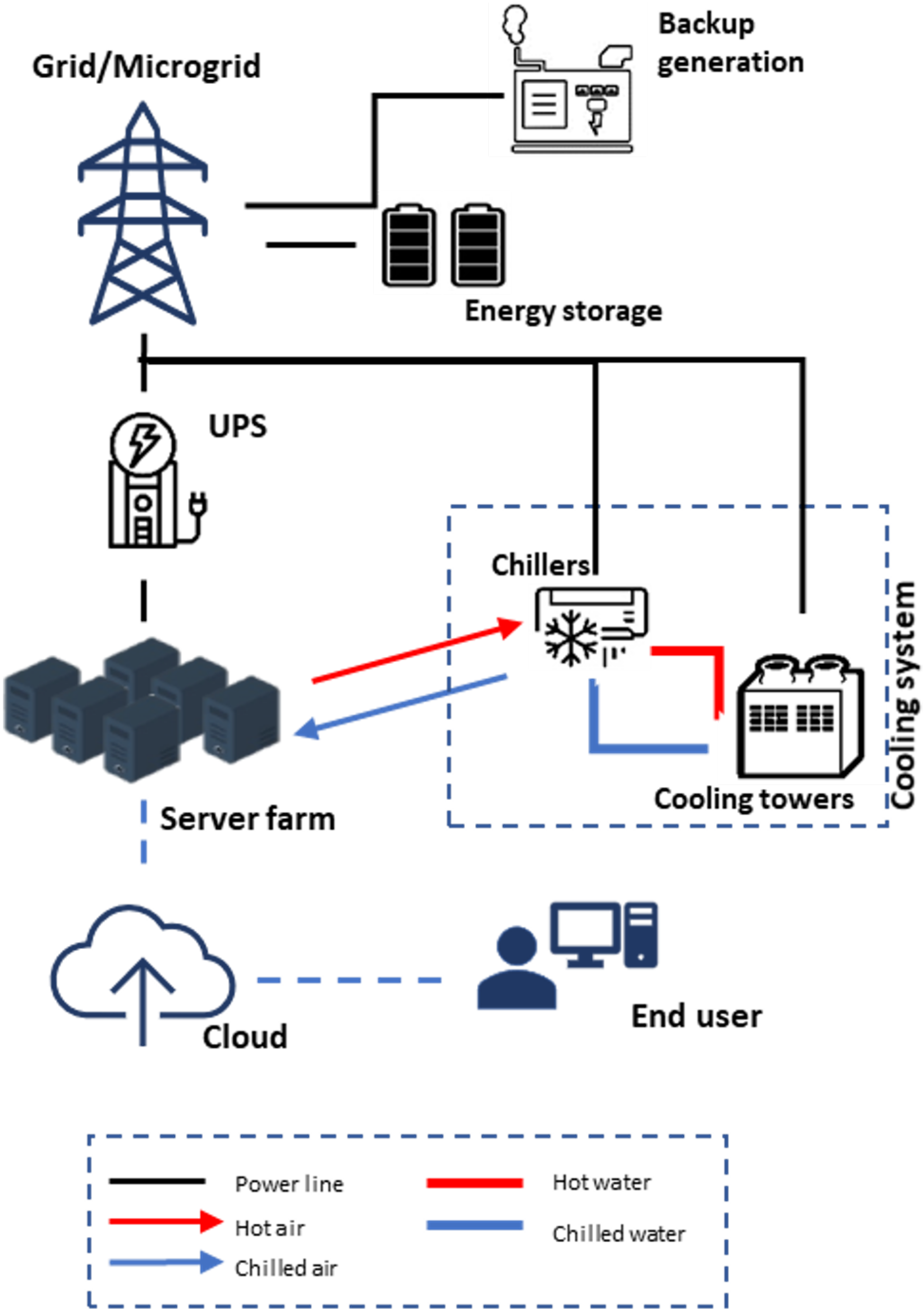

Figure 5. Basic components in a data center facility.

The year 2020 witnessed a 40% upsurge in global internet traffic, propelled by a proliferation in video conferencing, online gaming, and digital connectivity [37]. Forecasts suggest that by 2024, remote work will be integral to over 90% of infrastructure operations, and centralized platform engineering will be embraced by more than half of enterprises by 2025 [38]. This digitalization trajectory accentuates the imperative for robust data accessibility and security protocols, challenging to internalize within organizations.

Power reliability is critical, with outages having substantial financial repercussions, potentially costing up to USD 17,244 per minute [39]. Re-purposing underground mine sites as data centers presents a viable alternative, capitalizing on existing infrastructural elements like power lines and backup generators, essential for uninterrupted power supply (UPS) systems. The proposition for re-purposing the Osarizawa mine site underscores this potential.

Physical security complements cyber security in its importance, prompting some data centers to utilize underground facilities' inherent security advantages [37]. Examples include the Lefdal Mine Datacenter in Norway and the Bluebird Underground Data Center in Missouri, re-purposed from mining operations, offering natural cooling and fortified protection [40][41]. **Figure 6** shows the Lefdal Mine Datacenter, demonstrating its robust security features including a single point of entry.

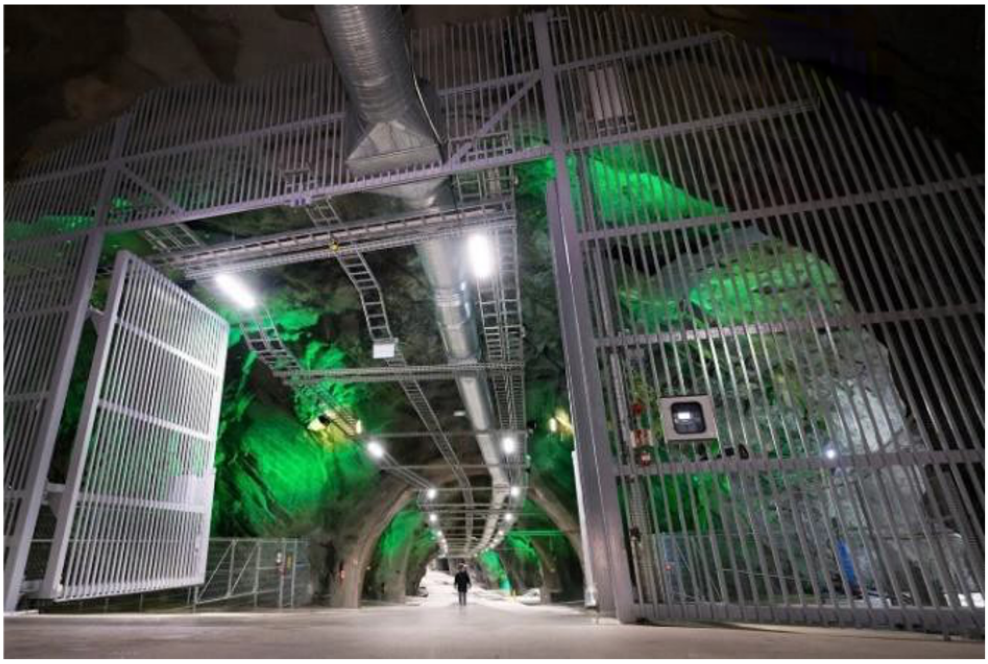

Figure 6. Lefdal Mine Datacenter has a single point of entry [21].

Innovative approaches extend to Microsoft's underwater data center, Project Natick, and proposed extraterrestrial data centers, aiming to exploit the natural cooling properties of these environments to reduce energy consumption [42][43]. **Figure 7** captures the retrieval of Microsoft's Northern Isles data center (Project Natick) in July 2020, showcasing its unique underwater environment.

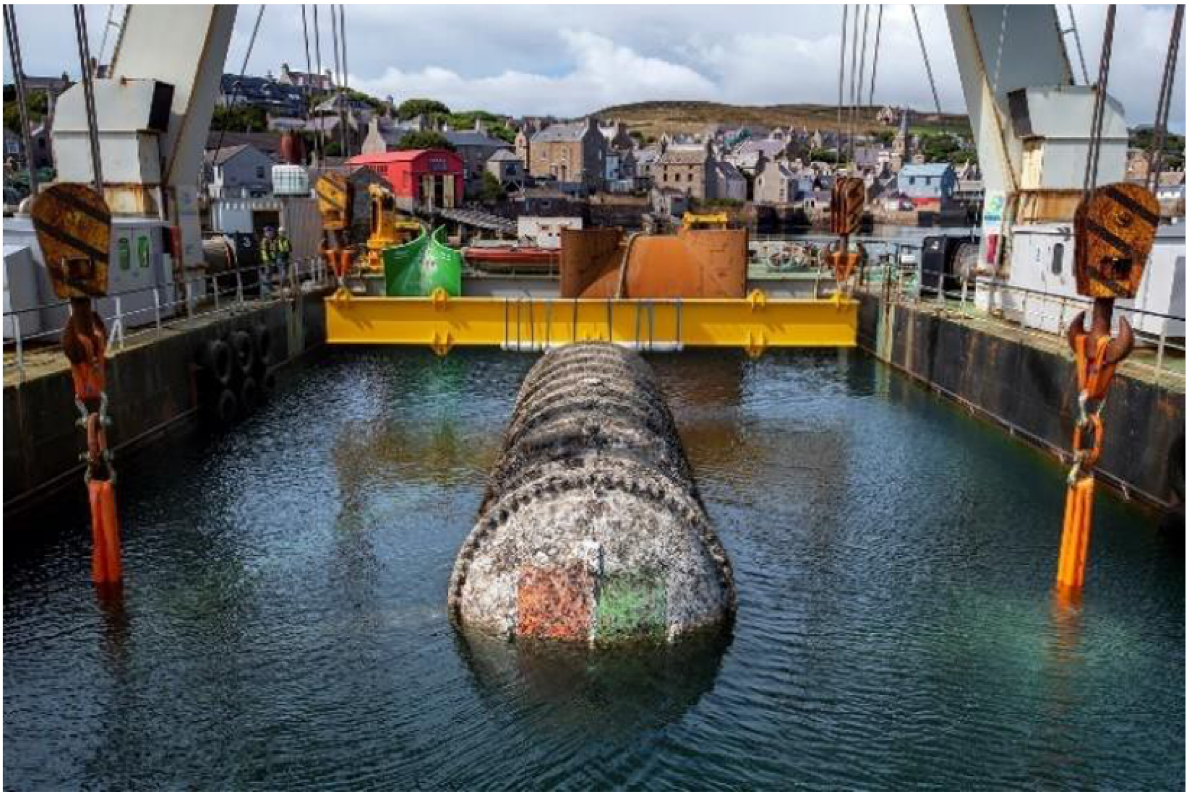

Figure 7. Retrieval of Microsoft's Northern Isles data center (Project Natick) in July 2020.

The integration of renewable energy sources and the conceptualization of data centers as heat sources for neighboring infrastructure further enhance their sustainability [44].

References

1. Fields, S. The earth's open wound: Abandoned and orphaned mines. Environ. Health Perspect. 2003, 111, A154.
2. World Bank. Mine Closure: A Toolbox for Governments; Technical Report; World Bank: Washington, DC, USA, 2021.
3. Wynn, M.; Lam, C. Digitalisation and IT Strategy in the Hospitality Industry. Systems 2023, 11, 501.
4. International Council of Mining and Metals ICMM. Closure Maturity Framework Tool for Closure User Guide; International Council of Mining and Metals ICMM: London, UK, 2020.
5. Likar, J.; Grøv, E. Underground citing of nuclear stations. In Underground—The Way to the Future, Proceedings of the World Tunnel Congress, WTC 2013, Edgbaston, Birmingham, UK, 23 June 2013; CRC Press: Boca Raton, FL, USA, 2013; pp. 27–34.

6. Holocombe, S.; Keenan, J. Mining as a Temporary Land Use Scoping Project: Transitions and Repurposing; Technical Report; The University of Queensland: Brisbane, Australia, 2020.
7. Ikeda, H.; Kawamura, Y.; Tungol, Z.P.L.; Molidi, M.A.; Jang, H. Implementation and Verification of a Wi-Fi Ad Hoc Communication System in an Underground Mine Environment. J. Min. Sci. 2019, 55, 505–514.
8. Ikeda, H.; Sato, T.; Yoshino, K.; Toriya, H.; Jang, H.; Adachi, T.; Kitahara, I.; Kawamura, Y. Deep Learning-Based Estimation of Muckpile Fragmentation Using Simulated 3D Point Cloud Data. Appl. Sci. 2023, 13, 10985.
9. Ikeda, H.; Malgazhdar, D.; Shionoiri, T.; Sinaice, B.B.; Adachi, T.; Kawamura, Y. Development of a Communication System for Underground Mining Informatization Leading to Smart Mining: A Comparison of Wi-Fi Ad Hoc and Wi-Fi Direct. J. Soc. Mater. Eng. Resour. Jpn. 2022, 25, 218–223.
10. Ikeda, H.; Kawamura, Y.; Jang, H.; Mokhtar, N.E.B.; Yokokura, J.; Tungol, Z.P.L. Development of an Underground In-Situ Stress Monitoring System for Mining Safety Using Multi Sensor Cell and Wi-Fi Direct Technology. In Proceedings of the 28th International Symposium on Mine Planning and Equipment Selection, Perth, Australia, 2–4 December 2019; pp. 236–244.
11. Ikeda, H.; Kolade, O.; Mahboob, M.A.; Cawood, F.T.; Kawamura, Y. Communication of sensor data in underground mining environments: An evaluation of wireless signal quality over distance. Mining 2021, 1, 211–223.
12. Bluhm, S.J.; von Glehn, F.H.; Marx, W.M.; Biffi, M. VUMA mine ventilation software. J. Mine Vent. Soc. S. Afr. 2001, 54, 65–72.
13. Webber-Youngman, R.C.W. An integrated approach towards the optimisation of ventilation, air cooling and pumping requirements for hot mines. In Proceedings of the Australasian Institute of Mining and Metallurgy Publication Series, Melbourne, Australia, 19–21 September 2005; pp. 75–84.
14. Sasmito, A.P.; Kurnia, J.C.; Birgersson, E.; Mujumdar, A.S. Computational evaluation of thermal management strategies in an underground mine. Appl. Therm. Eng. 2015, 90, 1144–1150.
15. Dahmen, U.; Rossmann, J. Experimentable Digital Twins for a Modeling and Simulation-based Engineering Approach. In Proceedings of the 4th IEEE International Symposium on Systems Engineering, ISSE 2018—Proceedings, Roma, Italy, 1–3 October 2018.
16. Sishi, M.; Telukdarie, A. Implementation of industry 4.0 technologies in the mining industry—A case study. Int. J. Min. Miner. Eng. 2020, 11, 1–22.
17. Cheskidov, V.V.; Lipina, A.V.; Melnichenko, I.A. Integrated monitoring of engineering structures in mining. Eurasian Min. 2018, 2018, 18–21.

18. Jacobs, D.R. Developing a Digital Twin for Addressing Complex Mine Ventilation Problems. Ph.D. Thesis, North-West University, Potchefstroom, South Africa, 2021.
19. Nie, X.; Wei, X.; Li, X.; Lu, C. Heat Treatment and Ventilation Optimization in a Deep Mine. Adv. Civ. Eng. 2018, 2018, 1529490.
20. Wagner, H. The management of heat flow in deep mines. Management von Wärmeströmen in tiefliegenden Bergwerken. Geomech. Tunn. 2010, 3, 609–621.
21. de Villiers, D.J.; Mathews, M.J.; Maré, P.; Kleingeld, M.; Arndt, D. Evaluating the impact of auxiliary fan practices on localised subsurface ventilation. Int. J. Min. Sci. Technol. 2019, 29, 933–941.
22. Schutte, A.J.; Kleingeld, M. An integrated energy efficiency strategy for deep mine ventilation and refrigeration. In Proceedings of the 2014 International Conference on the Eleventh Industrial and Commercial Use of Energy, Cape Town, South Africa, 19–20 August 2014.
23. Lu, Q.; Huang, G.; Ge, Y. Simulation of fire spreading in underground mine based on cellular automata and particle system. In Proceedings of the 2009 International Conference on Industrial Mechatronics and Automation, Changchun, China, 9–12 August 2009; pp. 180–183.
24. Danko, G.L. Subsurface flow and transport process model for time dependent mine ventilation simulations. Min. Technol. 2013, 122, 134–144.
25. Späth, M.B.; Conlan, O. VUMA: A Visual User Modelling Approach for the Personalisation of Adaptive Systems. Available online: http://kdeg.cs.tcd.ie/ (accessed on 19 November 2023).
26. Astrand, M.; Saarinen, K.; Sander-Tavallaey, S. Surrogate models for design and study of underground mine ventilation. In Proceedings of the 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, 12–15 September 2017; pp. 1–8.
27. Yang, W.; Yoshida, K.; Takakuwa, S. Digital Twin-Driven Simulation for a Cyber-Physical System in Industry 4.0 Era. In DAAAM International Scientific Book 2017; DAAAM International Vienna: Vienna, Austria, 2017; pp. 227–234.
28. Maré, P. Novel Simulations for Energy Management of Mine Cooling Systems. Ph.D. Thesis, North-West University, Potchefstroom, South Africa, 2017.
29. Holman, A.M.J.; van Rensburg, J.; Arndt, D. Benefits of site specific simulation models for assessing electrical energy savings potential on mine cooling systems. In Proceedings of the 10th Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 20–21 August 2013; pp. 1–6.
30. Fioroni, M.M.; dos Santos, L.C.A.; Franzese, L.A.G.; Santana, I.R.; Telles, G.D.; Seixas, J.C.; Penna, B.; de Alkmim, G.M. Logistic evaluation of an underground mine using simulation. In

Proceedings of the Winter Simulation Conference 2014, Savannah, GA, USA, 7–10 December 2014; pp. 1855–1865.

31. Genc, B.; Musingwini, C.; Celik, T. Estimating mine planning software utilization for decision-making strategies in the South African coal mining sector. J. S. Afr. Inst. Min. Metall. 2016, 116, 221–227.
32. Manríquez, F.; Pérez, J.; Morales, N. A simulation–optimization framework for short-term underground mine production scheduling. Optim. Eng. 2020, 21, 939–971.
33. McPherson, M.J. Subsurface Ventilation and Environmental Engineering; Springer: Dordrecht, The Netherlands, 1993.
34. Nel, A.J.H.; Vosloo, J.C.; Mathews, M.J. Evaluating complex mine ventilation operational changes through simulations. J. Energy S. Afr. 2018, 29, 22–32.
35. van Antwerpen, H.; Viljoen, D.; van der Meer, W.; Greyling, J. Combined system simulation of cooling and ventilation for the world’s deepest mine. In Proceedings of the Society of Mining and Exploration, Salt Lake City, UT, USA, 23–26 February 2014; pp. 1–10.
36. Wei, F.; Fangping, Z.; Huiqing, L. The Use of 3D Simulation System in Mine Ventilation Management. Procedia Eng. 2011, 26, 1370–1379.
37. MOUNT10—SWISS FORT KNOX. Available online: https://www.mount10.ch/en/mount10/swiss-fort-knox/ (accessed on 19 November 2023).
38. Chandrasekaran, A. Best Practices for Running Containers and Kubernetes in Production; Technical Report G00730344; Gartner: Stamford, CT, USA, 2019.
39. Ponemon Institute LLC. Cost of Data Center Outages. 2016. Available online: https://bit.ly/2nrfa3w (accessed on 19 November 2023).
40. Homepage—Lefdal Mine Datacenter. Available online: https://www.lefdalmine.com/ (accessed on 19 November 2023).
41. Bluebird Underground Data Center Services and Colocation Racks. Available online: https://bluebirdnetwork.com/underground-data-center (accessed on 19 November 2023).
42. Microsoft Finds Underwater Datacenters Are Reliable, Practical and Use Energy Sustainably|Innovation Stories. Available online: https://news.microsoft.com/innovation-stories/project-natick-underwater-datacenter/ (accessed on 19 November 2023).
43. Zhang, H.; Shao, S.; Xu, H.; Zou, H.; Tian, C. Free cooling of data centers: A review. Renew. Sustain. Energy Rev. 2014, 35, 171–182.
44. Paludetto, D.; Lorente, S. Modeling the heat exchanges between a datacenter and neighboring buildings through an underground loop. Renew. Energy 2016, 93, 502–509.

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