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Keynote Lecture

How AI and IoT are transforming geotechnical site monitoring and construction

Comment l'IA et l'IdO transforment la surveillance des sites géotechniques et la construction

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ABSTRACT: Artificial intelligence (AI) and internet of things (IoT) are the most transforming advancements in geotechnical site monitoring and construction. Indeed, the increasing integration of AI and IoT devices and technologies into construction processes have enhanced construction management as a benefit from real-time feedback that provides early warning systems, facilitating timely interventions and ensuring construction site safety, as well as structural health monitoring of built environment. This presentation will start summarising the state of the art of these advancements in geotechnical works. Two field works in Portugal, one on infrastructure earthworks and another on a metro line in an area of dense urbanisation with new and old buildings, including historical monuments, involving trenches, load transfer platform solutions and main station, serve to demonstrate the benefits of applying these developments in comparison to traditional management techniques.

RÉSUMÉ: L'intelligence artificielle (IA) et l'internet des objets (IdO) sont les technologies les plus transformatrices en matière de surveillance des sites géotechniques et de construction. En effet, l'intégration croissante des dispositifs et des technologies de l'IA et de l'IdO dans les processus de construction a amélioré la gestion de la construction grâce à un retour d'information en temps réel qui fournit des systèmes d'alerte anticipés, facilitant les interventions en temps réel et garantissant la sécurité du site de construction, ainsi que la surveillance de l'état structurel de l'environnement bâti. Cette présentation commencera par résumer l'état de l'art de ces avancées dans les travaux géotechniques. Deux chantiers au Portugal, l'un sur des travaux de terrassement d'infrastructures et l'autre sur une ligne de métro dans une zone d'urbanisation dense avec des bâtiments neufs et anciens, y compris des monuments historiques, impliquant des tranchées, des solutions de plate-forme de transfert de charge et la station principale, servent à démontrer les avantages de l'application de ces développements par rapport aux techniques de gestion traditionnelles.

Keywords: Artificial intelligence; internet of things; monitoring; earthworks; metro line.

1 INTRODUCTION

The Internet of Things (IoT) and Artificial Intelligence (AI) technologies offer immense potential for revolutionizing geotechnical monitoring, enhancing efficiency, accuracy, and safety across construction projects. By coupling IoT sensors with AI algorithms, geotechnical monitoring systems can collect vast amounts of data in real-time, enabling proactive decision-making, allowing to implement timely interventions and preventive measures to mitigate risks (Tan et al., 2022). In this context, A/D converters play a crucial role in this coupling by digitizing analogue signals from sensors, thus enabling the processing and analysis of data by AI algorithms. These converters bridge the gap between the physical world of sensor measurements and the digital facilitating the seamless operation of IoT-based monitoring systems. These systems exhibit the ability to detect structural impacts, monitor buildings through tilt sensors, and issue alerts upon surpassing predefined thresholds. Moreover, IoT generates novel datasets, revolutionizing risk assessment, design, construction, and maintenance practices (Kumar et al., 2023). Furthermore, AI algorithms analyse the data collected by IoT sensors to identify patterns, anomalies, and trends indicative of potential hazards, construction deficiencies or structural weaknesses. Machine learning techniques, such as neural networks or decision trees, among others, can learn from historical data to predict future events or assess the health status of the structural elements (Singh and Tyagi, 2023; Zhang et al., 2023). This predictive capability enhances the effectiveness of Early Warning Systems (EWS), enabling proactive measures to prevent catastrophic events (Kumar et al., 2023).

These developments that have emerged over the last decade are now maturing, offering significant advancements in construction site monitoring. These advancements primarily benefit from three key technologies: IoT, the availability of low-power, long-distance communication protocols, and the development of AI methods. These technological achievements enable the acquisition, transmission, and synthesis of geometric and structural geotechnical data, which are crucial for monitoring and mitigating risks on construction sites, especially in underground environments.

However, the integration of IoT, A/D converters and AI also presents challenges, including data privacy concerns, cybersecurity risks, and the need for interoperability among heterogeneous sensor networks (Liang et al., 2024). Addressing these challenges requires robust data governance frameworks, encryption protocols, and standardized communication protocols to ensure the reliability, security, and scalability of integrated geotechnical monitoring systems.

In this paper, we begin with this concise overview, underscoring the advantages of integrating IoT, A/D converters, and AI in geotechnical construction. Subsequently, we delve into a detailed exploration of emerging communication tools, web monitoring platforms, and AI applications. These considerations are contextualised within two field projects conducted in Portugal: one centred on transport infrastructure earthworks, and the other on a metro line located in an area marked by dense urbanization and a blend of new and historic structures, including monuments. The analysis underscores the superiority of these cutting-edge technologies when compared to conventional approaches and technologies.

2 EMERGING COMMUNICATION

Recent advances in geotechnical and structural monitoring are primarily linked to the emergence of wireless data transmission methods that are compatible with the scale of construction sites and make it possible to solve the recurring problem of powering sensors on these sites.

2.1 LoRaWAN radio networks

LoRaWAN (Long Range Wide Area Network) radio networks have gained significant attention in recent years for their ability to provide long-range, low-power communication suitable for various IoT applications, including geotechnical monitoring in construction projects. These networks operate on radio bands, offering excellent coverage even in challenging environments like urban areas or underground construction sites (Raza et al., 2017; Shanmuga Sundaram et al., 2020; Centenaro et al., 2016).

The LoRaWAN was developed in 2015 by the LoRa Alliance following research conducted from 2009 onwards in Grenoble, France (LoRa Alliance, 2024).

The LoRaWAN radio protocol has found unexpected applications in construction projects. Its key characteristics include the utilization of free and Europe-approved frequency bands, capable of transmitting data up to one kilometer in urban environments and up to 10 kilometers in open fields. Moreover, the protocol consumes minimal energy, and its limitations are compatible with geotechnical instrumentation, as geotechnical measurements are relatively low-frequency and require minimal digital space.

The LoRaWAN protocol enables the transmission of information from autonomous battery-powered sensors dispersed across the entire surface area of a construction site via radio, covering distances typical of extensive worksites for several years.

Deploying LoRaWAN networks necessitates the installation of fixed gateways and antennas to provide coverage for construction sites. This network of gateways must be managed by a "network core" linked to a supervision platform. This platform is essential for configuring the radio communication network, managing communications, and decrypting information received from the sensors.

LoRaWAN technology is not the sole low-power radio technology making strides in the construction sector; it is one of the LPWAN (Low Power Wide Area Network) communication technologies fueling the advancement of the IoT. Other promising communication protocols, such as LTE-M or NB-IoT, which utilise telephone operator infrastructures, are also emerging (Bajic et al., 2023; Malik et al., 2020; Rastogi et al., 2022). However, their adoption is currently limited by the availability of sensors compatible with these protocols.

2.2 Cellular communication and 5G

Significant advancements have been achieved in cellular communication technologies, facilitating their deployment in the niche yet rapidly expanding field of surveillance, which demands handling large data streams (such as acoustic measurements, vibration monitoring, real-time scanner tracking, video image analysis, etc.).

Particularly noteworthy progress has been made in managing cybersecurity risks associated with communication lines, eliminating coverage gaps, and optimizing communication throughput. It is worth noting that the advent of 5G communications, with their capacity for handling vast amounts of data, paves the way for numerous applications, albeit raising concerns regarding the sustainability of the volumes of data transmitted, analyzed, and stored.

3 WEB MONITORING PLATFORMS AND AI

Downstream, handling increasingly large data flows from construction sites has become feasible only with the emergence of robust, secure platforms capable of storing this data in data lakes. These platforms offer user-friendly, real-time internet access to pertinent, verified, translated, and summarized information for remote users with diverse needs.

The development of hosting platforms accessible in Software as a Service (SaaS) mode on trusted European clouds has facilitated high-speed access to technical information streams on all construction sites. This is done in compliance with cybersecurity and sovereignty requirements mandated by the General Data Protection Regulation (GDPR) and forthcoming AI Act regulations (CoC, 2020; CISPE, 2021).

One of the most promising aspects of these ongoing developments is the ability to train artificial intelligence models using the vast quantities of data collected from construction sites. These models can then operate in real-time to enhance the value of the gathered information. AI can now be leveraged for trend forecasting, expert filtering, and advanced alarms, offering powerful tools for engineers (Zhang et al., 2023).

Furthermore, AI has potential offline applications, particularly in information synthesis and construction design.

Again, it is crucial to emphasize the ethical and environmental implications of AI usage (Liang et al., 2024). The storage and processing of vast amounts of information for AI model creation require significant energy consumption, contributing to companies' carbon footprints and potentially hindering efforts to combat climate change. The benefits of AI usage must be balanced against the carbon cost of its production.

Moreover, significant ethical risks may arise during the development of AI models. The AI Act provides valuable clarification by categorizing applications into four distinct risk levels (unacceptable, high, low, minimal), thereby enabling the responsible use of AI models with minimal ethical risks in the construction sector (Taddeo and Floridi, 2018).

4 APPLICATION TO EARTHWORKS – CASE STUDY

Earthwork processes often encounter significant uncertainties, requiring flexibility from planning and management teams to address unforeseen events like severe weather or equipment failures. Successful solutions for these challenges relies heavily on the expertise of the teams involved. However, since this expertise is not always readily available, decision support systems become invaluable. These systems not only compile and organize knowledge and experience from past projects but also foster collaboration across different specialties and teams throughout all phases of construction projects, aligning with modern concepts like Construction 4.0 and Building Information Modeling (Han et al., 2022).

In the context of earthworks, decision support systems serve various purposes, from predicting material behavior and equipment productivity to monitoring equipment positioning and optimizing resource allocation (Gomes Correia et al., 2013; Gomes Correia, 2018; Marques et al., 2008; Parente et al., 2015, 2016, 2018). These systems leverage on technologies such as artificial intelligence, simulation, and optimization algorithms, to tackle different problems and objectives (Choi and Han, 2023).

To illustrate the effectiveness of these systems, a real case study from Portugal involving road construction is presented (Neves et al., 2024). This study aimed to optimize resource allocation across multiple construction and excavation fronts, minimizing costs and project duration through multi-objective optimization (Jaafar and El-Halawani, 2022).

4.1 Technologies

In the specific case of earthworks, decision support is generally sought in order to predict (e.g., behavior of geomaterials, slope safety, equipment productivity as a function of working conditions), monitor (e.g., position of transport equipment, downtime, mechanical breakdowns), and/or optimize (e.g., distribution of geomaterial volume between excavation and embankment fronts, minimization of transport distances, optimal allocation of mechanical resources).

Based on technologies such as artificial intelligence, simulation, optimization algorithms, and sensing, these systems can be divided according to the methodology adopted and the objectives of decision support.

On the one hand, there is planning support, typically based on forecasting or robust optimization systems, which aim to create robust plans that not only encompass the predictable work to be carried out, but also include contingency plans for potential disruptive situations. On the other hand, there is construction support, focused on monitoring and reactive optimization systems, which advocate maximum flexibility in adjusting the initial plan in response to more volatile environments or the possibility of unforeseen occurrences.

Figure 1 shows the workflow of the optimization system paired with IoT system for earthworks projects. In the following subsection, it is presented an illustrative example of the potential of this type of systems in planning and construction phases, respectively, adopting as reference a real case study associated with the earthwork phases of a road construction project in Portugal. The project consisted of 24 embankment construction fronts, fed by 15 excavation fronts. The total volume of processed geomaterial was approximately 1,500,000 m^3 over an approximate extension of 20 km of highway, with the average estimated duration of the work being approximately 6 months. The equipment fleet consisted of a total of 6 compactors, 14 spreading equipment, 29 excavators, and 39 geomaterial transport trucks.

For this application, a simulation of conditions close to real was carried out, using only the aforementioned available resources to develop the work according to the practices already commonly used in the industry. The adopted methodology described in Neves et al. (2024) was based on the work developed by Correia and Magnan (2012), Parente et al. (2018, 2022), aiming to find optimal solutions for the allocation of equipment fleet by work fronts and over time, simultaneously minimizing costs and work execution duration (multi-objective optimization).

4.2 Application to planning/design

As previously mentioned, the aim of this simulation was to showcase the potential of integrating these technologies for optimal equipment fleet allocation. Given the dynamic nature of the problem, with multiple work fronts such as excavations/ cuts and embankments progressing simultaneously, the solution must also be dynamic. This means that as teams complete work on one front, they need to transition to another, considering factors like varying transport distances, types of geomaterials, and available space. To achieve these objectives, the system requires input on available mechanical resources, including compactors, spreaders (e.g., bulldozers, graders), excavators, and transport trucks, along with specifications for each. Additionally, information on the work to be carried out, such as excavation and embankment fronts, their locations, types, volumes of associated geomaterials, and maximum number of active equipment, is needed. With access to this data, the optimization algorithm, based on a non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002), seeks the best resource allocation solution throughout the project.

The multi-objective optimization process encompasses multiple stages. These range from the choice of the optimal distribution of geomaterial volumes between fronts, while minimizing transportation distances (which can alternatively be defined by the user based on project requirements), to the optimal allocation of all available equipment over time throughout the workfronts, adopting a scheduling methodology that defines where each equipment should be and for how long, resulting in the minimization of global execution costs and duration. The process takes approximately 3 hours in a conventional laptop (in this case, Intel i7-10750H 2.60GHz, with16GB RAM and running Windows 11) and presents solutions in a Pareto format. Each point on the Pareto front represents an equipment allocation, evaluated based on duration and cost (Figure 2). These solutions offer optimal trade-offs between time and cost, allowing flexibility in decision-making.

Results can be accessed in various formats, such as spreadsheets or maps, enabling visualization of equipment allocation for each work phase. This facilitates analysis of different scenarios and selection of the best option based on time, cost, and allocation details provided for each solution.

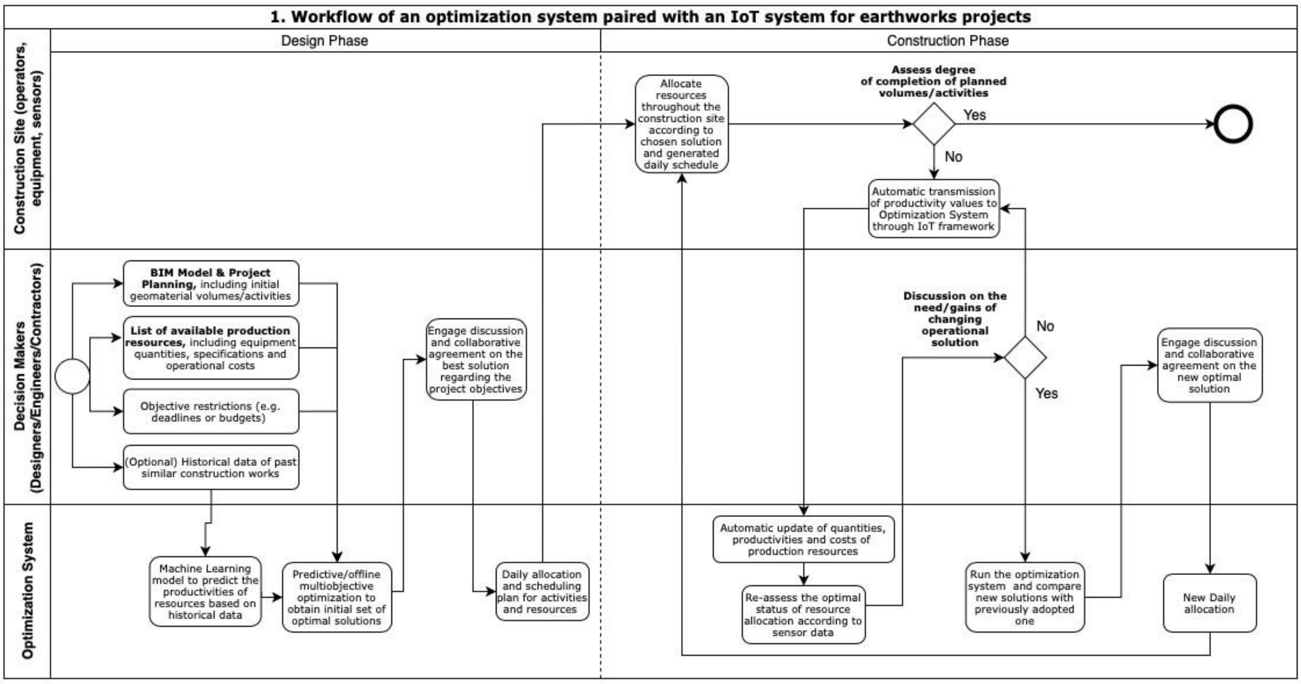
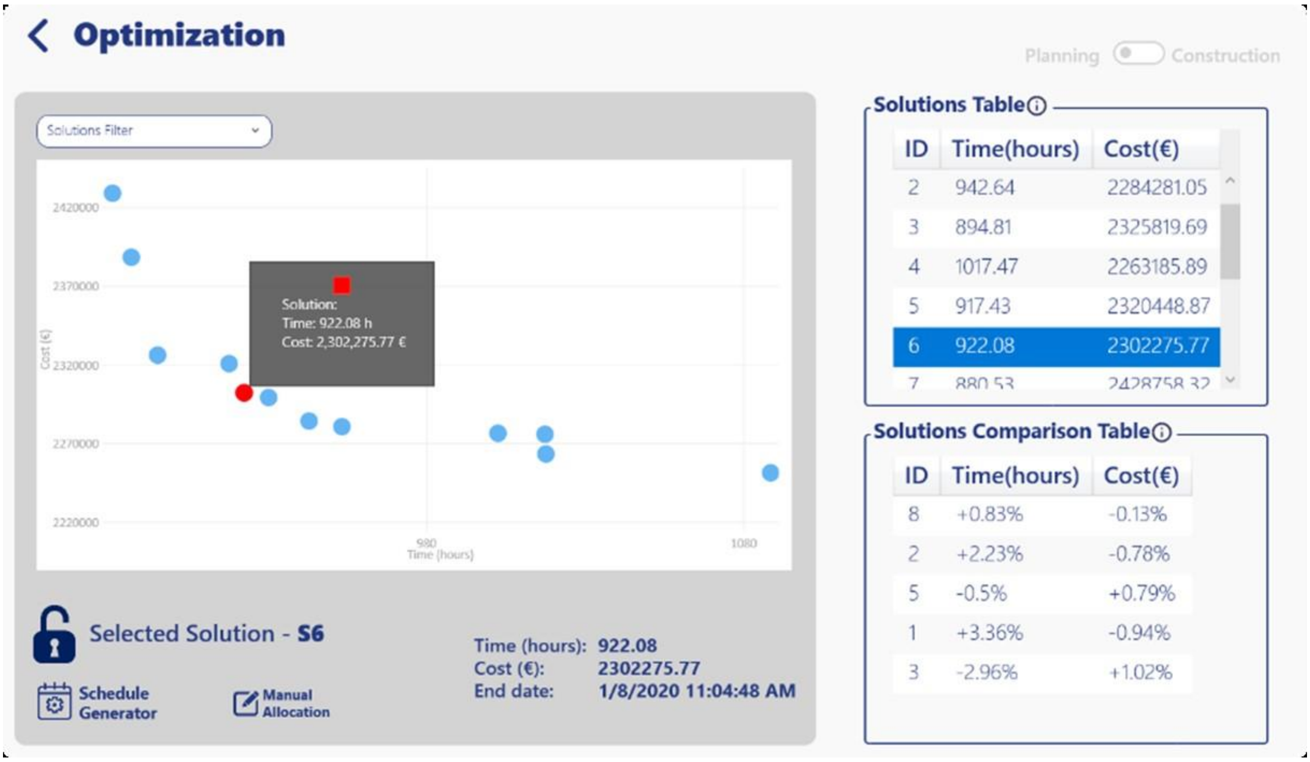


Figure 1. Workflow of the optimization system paired with IoT system for earthworks projects.



Solutions Table

ID	Time(hours)	Cost(€)
2	942.64	2284281.05
3	894.81	2325819.69
4	1017.47	2263185.89
5	917.43	2320448.87
6	922.08	2302275.77
7	880.53	2428758.32

Solutions Comparison Table

ID	Time(hours)	Cost(€)
8	+0.83%	-0.13%
2	+2.23%	-0.78%
5	-0.5%	+0.79%
1	+3.36%	-0.94%
3	-2.96%	+1.02%

Selected Solution - **S6**

Time (hours): **922.08**
Cost (€): **2302275.77**
End date: **1/8/2020 11:04:48 AM**

Figure 2. Pareto front solutions output from the planning/design phase of the system.

4.3 Application to construction phase

This simulation incorporates GPS positioning sensors in transport trucks during construction, enabling productivity assessment based on cycle counts within specified periods. This system also infers excavation and compaction team efficiency during loading and unloading cycles. These assessments are conducted with minimal intervention, as GPS is only installed on the transport trucks. Initially, productivity measurements are indicative, assuming trucks are fully loaded. However, these values are adjusted monthly based on topographic measurements at each work front. These measurements, part of regular quality control processes, provide accurate volumes of excavated and embanked geomaterials, allowing for comparison with system estimates.

To address variations between actual and estimated volumes, a corrective factor, 'k', is applied to truck productivity. This factor is proportional to the ratio of actual volumes measured topographically to those estimated by the system. The system operates in monitoring and control mode from the beginning of the construction phase. A control dashboard offers real-time project progress monitoring, productivity tracking at each work front, and live transport equipment location updates (Figure 3). It also issues notifications for potential issues and provides access to activity history and project parameters.

In case of project changes, such as equipment breakdowns or alterations to material types, the system recalculates costs and duration for subsequent phases. Users can choose to accept revised forecasts or request resource reallocation to optimize work efficiency.

During re-optimization, a third minimization objective, Re-Allocation Disruption (RAD), considers the cost of reallocating equipment between work fronts. RAD minimizes disruptions caused by equipment changes, optimizing the reorganization process. In both planning/design and construction phases, the system not only allocates resources but also selects the optimal fleet, ensuring efficient resource utilization. Nomenclature for solutions in re-optimization facilitates tracking of adjustments throughout the project. The system maintains a descriptive database of project development, enabling future analyses and applications of artificial intelligence for knowledge extraction. It can also illustrate the normal operation of the control dashboard, offering a comprehensive overview of project status, productivity metrics by work front, real-time transport equipment tracking via map visualization, and notifications for potential issues. This dashboard also provides access to activity history and project parameter editing functions.

In the event of re-optimization, the system generates a new set of solutions, with each solution evaluated based on minimization objectives, once again presented in Pareto format. The system adjusts solutions dynamically, accounting for changes in project conditions and constraints.

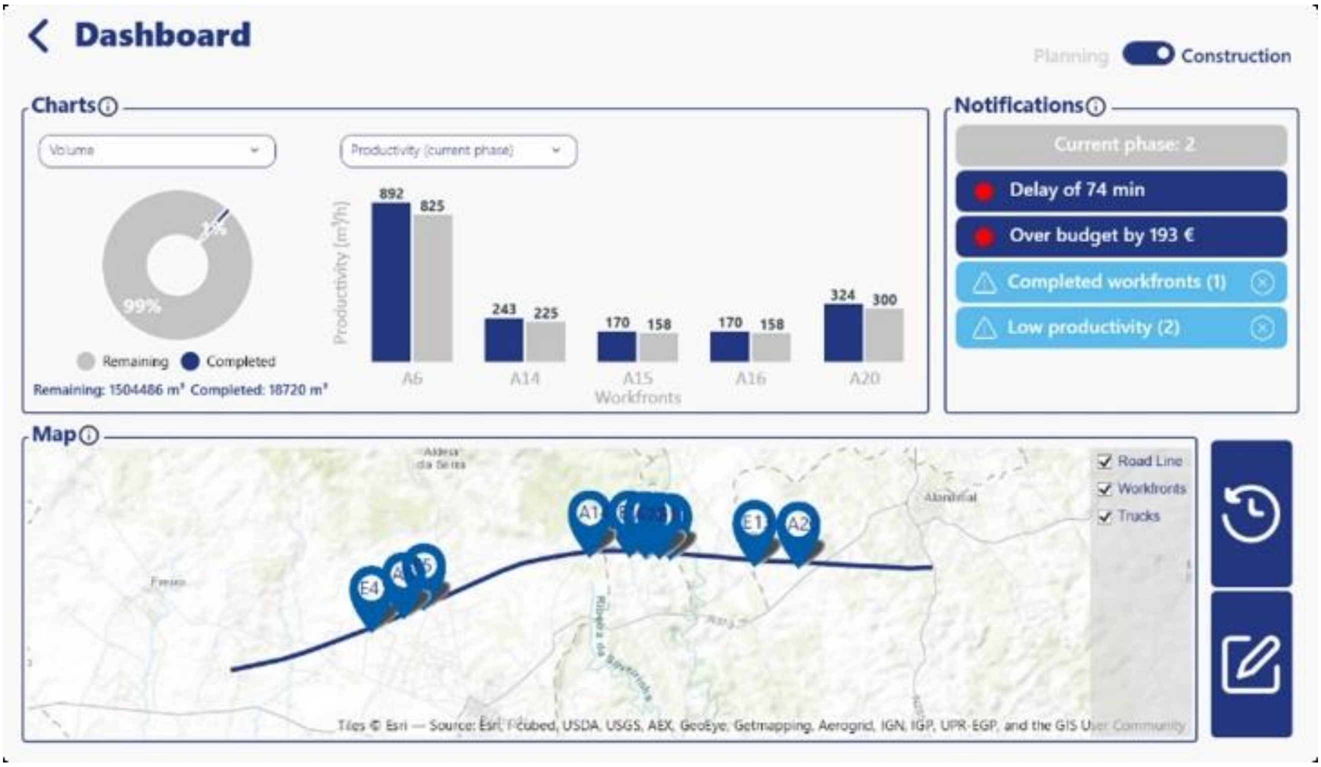


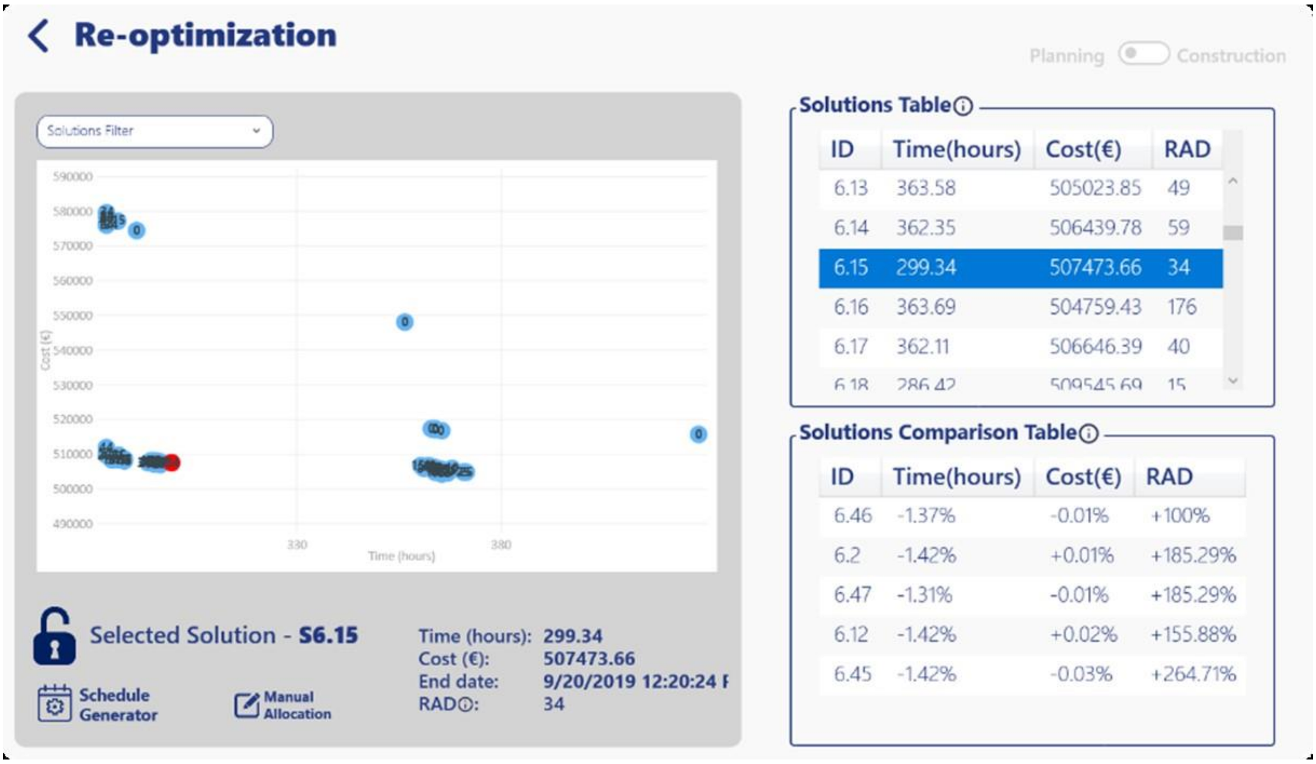
Figure 3. Monitoring and control dashboard for the conducted construction simulation.

Figure 4 displays the allocation adjustments resulting from re-optimization. Each solution corresponds to a specific equipment allocation, evaluated by associated duration and cost metrics. The system also evaluates the Re-Allocation Disruption (RAD) associated with each solution, providing additional decision support for users.

4.4 Intelligent compaction

The concept of Industry 4.0 (i4.0) offers new opportunities for intelligent optimization of compaction operations (Parente et al., 2018; Gomes Correia, 2018). By leveraging smart sensors and real-time monitoring, i4.0 enables the creation of virtual models to simulate compaction processes and continuously assess geomaterial properties. Machine learning algorithms enhance predictive capabilities and facilitate classification of geomaterials based on their properties, leading to improved compaction quality.

Figure 5 illustrate the most representative tools of i4.0 applied in intelligent compaction (Gomes Correia, 2018).



Selected Solution - **S6.15**

Time (hours): **299.34**
Cost (€): **507473.66**
End date: **9/20/2019 12:20:24 F**
RAD: **34**

Solutions Table

ID	Time(hours)	Cost(€)	RAD
6.13	363.58	505023.85	49
6.14	362.35	506439.78	59
6.15	299.34	507473.66	34
6.16	363.69	504759.43	176
6.17	362.11	506646.39	40
6.18	286.42	509545.69	15

Solutions Comparison Table

ID	Time(hours)	Cost(€)	RAD
6.46	-1.37%	-0.01%	+100%
6.2	-1.42%	+0.01%	+185.29%
6.47	-1.31%	-0.01%	+185.29%
6.12	-1.42%	+0.02%	+155.88%
6.45	-1.42%	-0.03%	+264.71%

Figure 4. Pareto front solutions output of adjustments that arise from the re-optimization process.

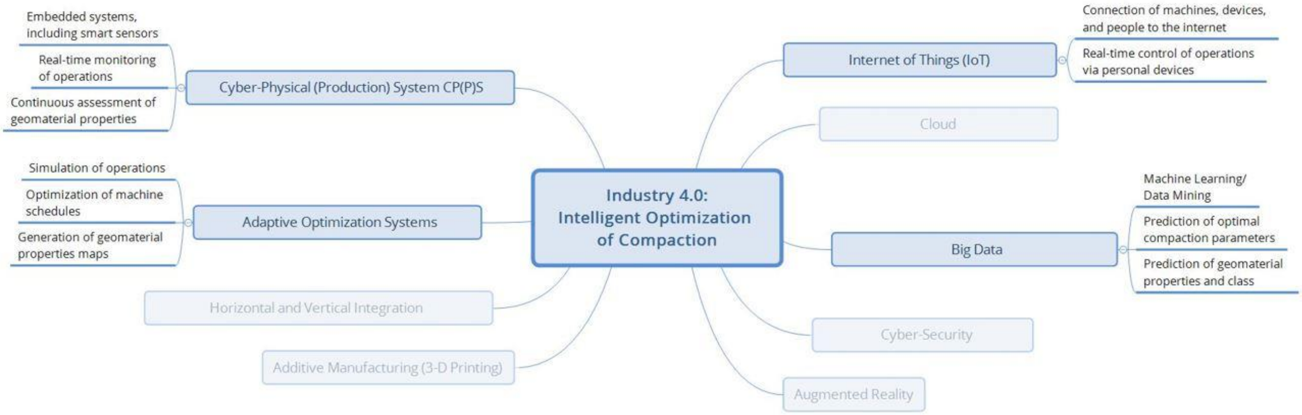


Figure 5. Industry 4.0 technologies applied to intelligent optimization of compaction.

Indeed, this approach can provide an agile and autonomous decision-making facing the challenges posed by dynamic and unpredictable environments, such as those encountered in compaction operations. To achieve this, it prioritises the utilisation of technologies like smart sensors for real-time monitoring of the compaction process. This enables the creation of a virtual representation of physical compactors within a simulation model and facilitates continuous assessment of geomaterial properties and continuous compaction control. Indeed, unlike traditional methods that may only sample certain areas, these technologies can monitor and assess the entirety of the compacted area in real-time.

On one hand, this forms the foundation for real-time scheduling and optimization of compactor tasks, while simultaneously processing the feedback data from the geomaterial. On the other hand, this data can also be subjected to machine learning and data mining algorithms. These techniques not only enable the prediction of optimal compactors parameters but also allow for the continuous compaction control and classification of geomaterials based on their properties, the so-called intelligent compaction (IC). This offers opportunities for further enhancement and refinement of the compaction process and deliver quality control parameters that can be directly compared with design parameters (Tatsuoka and Gomes Correia, 2018; Gomes Correia and Ramos, 2022).

Furthermore, this entire process is underpinned by the connectivity of compactors, devices, and personnel to the internet, aligning with the principles of the Internet of Things (IoT). This connectivity fosters transparency, enhances communication, and facilitates real-time control of operations from any location worldwide with internet access, using personal communication devices such as smartphones.

In summary, intelligent compaction emerges as a pivotal technology, particularly during the construction phase, facilitating automated functions such as perception, analysis, decision-making, and execution (Xu et al., 2022). This technology holds significant importance in global engineering construction endeavours. At its core, intelligent compaction plays a crucial role in accurately perceiving compaction quality information, involving dynamic solutions to the interaction between rigid cylinders and elastic half-spaces (Paulmichl et al., 2022). However, there remains a need for further exploration to meet the precision requirements of quality control and dynamic solutions in this area. In this context, the integration of intelligent compaction within the previously discussed optimization framework holds significant promise for enhancing the efficiency and effectiveness of earthwork projects. It will improve project management by enabling proactive decision-making based on accurate and up-to-date information. For instance, the optimization system can dynamically adjust compactor routes and operating parameters in response to variations in soil type, conditions, or unexpected obstacles encountered during construction. By analysing compaction data in real-time, the system can identify areas of suboptimal compaction and allocate resources accordingly to ensure uniform compaction, thereby ensuring consistent compaction levels and meeting specified engineering design criteria across the entirety of the construction site.

5 APPLICATION TO AN URBAN METRO LINE – CASE STUDY

The Lisbon metro construction site, spanning between Santos and Cais do Sodre stations, serves as an intriguing showcase for the utilization of these technologies. This multifaceted construction project faces numerous challenges, including the construction of a sizable station on the urban side of the Santos hill, the excavation of a traditional tunnel within Lisbon's historic district, the creation of a trench in a densely populated urban area adjacent to sensitive buildings, the building underpinning through which the line passes, and the seamless integration with the operational station at Cais do Sodre. More detailed information is available at Martins et al. (2024).

Addressing these diverse challenges necessitated the implementation of an advanced monitoring system comprising robotic measurements, IoT sensors, a web platform, and real-time processing leveraging artificial intelligence. Figure 6 identify the monitoring devices (liquid level sensor and extensometer) for the specific case of underpinning building, solution adopted to facilitate the deactivation of the foundation piles of existing buildings within the tunnel projection area and to start excavation for the construction of the tunnel structure, part of Lisbon Metro line - new circular line.

5.1 Database process

The ARGOS platform was selected to centralize, store in Software as a Service (SaaS) mode, and manage monitoring data for the entire site during the extension of the works. The measurements encompass a wide range of data types, including manual and automatic topographic measurements, convergence measurements, borehole extensometer measurements, stress measurements, crack openings, altimetric liquid level monitoring, piezometric measurements, inclinometric measurements, and automatic high-end vibration measurements.

Figure 6. Lisbon Metro line new circular line: Underpinning building - Monitoring devices.

5.2 Monitoring data management and visualisation

All data are securely stored on a hyper-secure, trusted European cloud that complies with GDPR as well as European requirements regarding artificial intelligence. These data are accessible in real-time through a responsive web interface, presented in various formats such as plans, multi-layer GIS interfaces, dynamic maps, 3D views, dashboards, graphs, and reports.

5.2.1 Sensors technologies, wireless, communication protocols, cloud platform

The extensive coverage of the site, combined with the high number of sensors and measurement frequencies, along with the presence of various challenging traffic lanes, necessitated the adoption of automated measurements for the robotic theodolites, vibration sensors, and geotechnical and structural IoT sensors.

To ensure comprehensive coverage, both above and below ground, a network of radio bases was deployed across the entire site. Managed by the ARGOS core network, this radio network facilitates the secure and encrypted transmission of field data back to the central system.

5.2.2 Prediction models and anomaly detection

All raw data are securely transmitted to the cloud-based database where they undergo real-time processing to generate actionable information for the users.

Raw measurements may not always be immediately usable due to various reasons. These could include the need for transformation of electrical data for comprehension, presence of statistical errors such as artifacts or parasites, or excessively high data flow rates that are impractical for direct analysis by engineers. For instance, in the field of vibration monitoring, each instrument may generate thousands of measurements per second, which must be condensed into manageable indicators for site monitoring purposes.

In addressing these challenges, the monitoring platform assumes a critical role in real-time data processing. It employs mathematical, statistical, and logical algorithms, as well as artificial intelligence models, to perform tasks such as summarizing data, reducing noise, and making real-time forecasts based on historical data. For example, artificial intelligence algorithms can be trained to recognize and eliminate erroneous topographical data, enhancing the reliability of the information delivered and fortifying the overall robustness of the monitoring system. This sophisticated tool leverages the expertise of topographic engineers to ensure the integrity and accuracy of the monitoring data.

5.2.3 Alerts and actions

Once processed, the availability of reliable real-time measurements forms the cornerstone of effective site risk management. Customized detection thresholds are established for each sensor, triggering advanced alarms instantly upon their surpassing. These alarms are configured with various levels of sensitivity, conditional triggers, differentiated responses based on thresholds, schedules, and alarm groupings, among other details tailored to the site's configuration and management requirements. Table 1 illustrates the criteria for alerts, references, and alarms utilized for monitoring settlements in column 10 (Figure 6) of the building during load transfer operations as part of the underpinning process. These settlements are associated with the load step values applied by the jacking.

Table 1. Lisbon Metro line new circular line: Underpinning building - Monitoring thresholds for column 10.

Column	Estimated Load (kN)	Load step	Load (kN)	Settlement measured in Liquid Level Sensors (mm)		
				Alert	Reference	Alarm
10	3362	10%	336	0,4	0,5	0,6
		20%	672	0,7	0,8	1,1
		30%	1008	1,0	1,2	1,6
		40%	1344	1,4	1,7	2,3
		50%	1680	1,8	2,2	2,9
		60%	2016	2,1	2,5	3,4
		70%	2353	2,5	3,0	4,1
		80%	2689	2,8	3,4	4,5
		90%	3025	3,1	3,7	5,0
		100%	3362	3,5	4,2	5,7

The alarms activated by the ARGOS platform are integrated into a comprehensive action plan detailing proactive and corrective measures to be taken when thresholds are breached. Upon activation, the ARGOS software promptly dispatches notifications in real time to designated stakeholders, providing details of the triggered alarm, the observed value, and the timestamp of the occurrence.

This proactive approach enables the site management team to swiftly intervene and mitigate any potential risks that could jeopardize the safety of personnel or structures within the construction site perimeter.

6 CONCLUSIONS

The integration of IoT and AI technologies in geotechnical engineering has led to the development of advanced Early Warning Systems (EWS) capable of real-time communication of critical events. These technologies facilitate efficient monitoring through reliable connections between sensors, control units and communication methods. Challenges include scalability, sustainability, and security. Best practices involve integrating AI-powered systems that can collect vast amounts of data in real-time and analyse it to provide actionable insights. By analysing trends and correlations in the data, AI models can forecast potential incidents and trigger early warning systems, allowing for proactive intervention and risk mitigation measures.

Earthwork construction projects often face uncertainties, requiring flexibility from planning and management teams to handle unforeseen events like weather changes or equipment failures. Decision support systems play a vital role by compiling past knowledge and facilitating collaboration among teams, aligning with modern construction principles like Construction 4.0 and Building Information Modelling (BIM). These systems utilize technologies like artificial intelligence and optimization algorithms to predict, monitor, and optimize earthwork processes.

A case study from a road construction project in Portugal illustrates how these systems optimize equipment fleet allocation, considering factors like cost, duration, and resource availability. In planning, the system creates robust plans with contingency measures, while during construction, it monitors productivity and adapts to disruptions. Historical data from projects enable future analysis and knowledge extraction, contributing to continuous improvement in earthwork construction.

In this context, intelligent compaction, as part of earthworks, leverages IoT and AI technologies to enhance the efficiency and effectiveness of soil compaction processes. Furthermore, the application of the previous optimization systems for earthworks, allows for informed decision-making by dynamically adjusting compaction equipment deployment and work schedules based on compaction performance. Smart sensors allow monitor compaction in real-time, providing data for optimization of the compaction. AI algorithms analyse this data to predict optimal parameters of the interaction roller-soil, and classify soil types, improving compaction quality and allowing assessment of design parameters. IoT connectivity enables remote monitoring and control, enhancing transparency and communication throughout all the earthwork process.

A second case study involving a metro construction site in Lisbon, illustrates also the use IoT and AI. In this case, the data, securely stored on a trusted European cloud complying with GDPR and AI regulations, are made accessible in real-time via a responsive web interface, offering various formats like plans, GIS interfaces, dynamic maps, and dashboards. To cover the extensive site and high sensor count, automated measurements using robotic theodolites, vibration sensors, and IoT sensors were deployed, managed by the ARGOS core network. Raw measurements undergo real-time processing to produce actionable insights, overcoming challenges like data transformation and high flow rates. A monitoring platform employs AI to enhance data reliability, recognizing and eliminating errors. Customized thresholds trigger advanced alarms, enabling proactive risk management. Notifications alert stakeholders to potential risks, ensuring swift intervention to maintain site safety.

As a concluding note, the couple of IoT and AI technologies presents unparalleled prospects for transforming geotechnical construction and management methodologies. This synergy heralds the era of safer and more resilient project developments, delivering substantial advantages for all the players across the design, construction, and maintenance sectors, ultimately enhancing societal well-being.

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REFERENCES

Bajic, E., Mekki, K. and Rup, C. (2023). LTE-M communication for low-powered IIoT: An experimental performance study. *17th International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, UBICOMM 2023, Sep 2023, Porto, Portugal. Available at: https://hal.science/hal-04222955, accessed: 01/04/2024.

Centenaro, M., Vangelista, L., Zanella, A. and Zorzi, M. (2016). Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios. IEEE Wireless Communications, 23 (5): 60-67. https://doi.org/10.1109/MWC.2016.7721743.

Choi, G. and Han, S. (2023). Reinforcement learning-based dynamic planning of cut and fill operations for earthwork optimization. *Automation in Construction*, 156. https://doi.org/10.1016/ j.autcon.2023.105111.

CISPE (2021). Data Protection Code of Conduct for Cloud Infrastructure Service Providers, available at: https://www.edpb.europa.eu/system/files/2023-03/2021_cispe_cloud_iaas_data_protection_code_of_conduct_-_gdpr_compliance_0.pdf, accessed: 01/04/2024.

CoC (2020). EU Data Protection Code of Conduct for Cloud Service Providers, December 2020, available at: https://eucoc.cloud, accessed: 01/04/2024.

Correia, A. G. and Magnan, J-P. (2012). Trends and challenges in earthworks for transportation infrastructures. Advances in Transportation Geotechnics II (Seiichi Miura et al., eds.). *Proceedings of the 2nd International Conference on Transportation Geotechnics*, Hokkaido , Japan, ICTG 2012, pp. 1 – 12. Taylor and Francis – Balkema. https://doi.org/10.1201/b12754.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans Evol Comput*, 6, pp. 182–197.

Gomes Correia, A. (2018). Extended 2nd Proctor Lecture: Compaction improvements from an Industry 4.0 perspective. *40 Years of Roller Integrated Continuous Compaction Control (CCC) - Anniversary Symposium*, by Adam, D., & Larsson, S. (Eds.). November 29th, 2018 - Symposium Proceedings. Mitteilungen des Institutes für Geotechnik. http://hdl.handle.net/20.500.12708/24485.

Gomes Correia, A. and Ramos, A. (2022). A geomechanics classification for the rating of railroad subgrade performance. *Railway Engineering Science*, 30 (3): 323 – 359. http://doi.org/10.1007/s40534-021-00260-z.

Gomes Correia, A., Cortez, P., Tinoco, J. and Marques, R. (2013). Artificial intelligence applications in transportation geotechnics. *Geotechnical and Geological Engineering*, Springer, 31(3): 861-879. http://doi.org/ 10.1007/s10706-012-9585-3.

Han, T., Ma, T., Fang, Z., Zhang, Y. and Han, C. (2022). A BIM-IoT and intelligent compaction integrated framework for advanced road compaction quality monitoring and management. *Computers and Electrical Engineering*, 100. https://doi.org/10.1016/j.compeleceng.2022. 107981.

Jaafar, K. and El-Halawani, L.I. (2022). Simulation-based multi-objective optimization model for machinery allocation in shallow foundation. *International Journal of Construction Management*, 22 (15): 2845 – 2854. ttps://doi.org/10.1080/15623599.2020.1827693.

Kumar, G.S.A., Roy, A., Singh, R., Gehlot, A., Iqbal, M.I. and Akram, S.V. (2023). A comprehensive approach to real-time site monitoring and risk assessment in construction settings using Internet of Things and artificial intelligence. *SSRG International Journal of Electrical and Electronics Engineering*, 10 (8): 112 – 126. https://doi.org/10.14445/23488379/IJEEE-V10I8P111.

Liang, C-J., Le, T-H, Ham, Y., Mantha, B.R.K., Cheng, M. H. and Lin, J.J. (2024). Ethics of artificial intelligence and robotics in the architecture, engineering, and construction industry. *Automation in Construction*, 162. https://doi.org/10.1016/j.autcon.2024.105369.

LoRa Alliance (2024). Available at: https://lora-alliance.org/, accessed: 01/04/2024.

Malik, H., Alam, M.M., Kuusik, A., Le Moullec, Y. and Pärand, S. (2020). Narrowband Internet of Things (NB-IoT) for industrial automation. *Wireless Automation as an Enabler for the Next Industrial Revolution* (eds M.A. Imran, S. Hussain and Q.H. Abbasi). https://doi.org/ 10.1002/9781119552635.ch4.

Marques, R., Gomes Correia, A. and Cortez, P. (2008). Data mining applied to compaction of geomaterials. Eight International *Conference on the Bearing Capacity of Roads, Railways and Airfields*, Champaign, Illinois, USA.

Martins, C., Fartaria, C., Tomásio, R. and Pinto, A. (2024). Lisbon new circular Metro underground line: Buildings underpinning. Proceedings of the *XVIII ECSMGE 2024*, Lisbon, Portugal. CRC (in press).

Neves, J., Moutinho, J., Freire, A.C., Paixão, A., Monteiro, B., Parente, M. and Gomes Correia, A. (2024). A geotecnia na transição eco-digital das infraestruturas de transporte (Geotechnics in the eco-digital transition of transport infrastructures). *Geotecnia*, Número Extra (2024): 41-78. https://doi.org/ 10.14195/2184-8394_extra2024_1_3 (in Portuguese).

Parente, M., Correia, A.G. and Cortez, P. (2016). Metaheuristics, Data mining and geographic information systems for earthworks equipment allocation. *Procedia Engineering*, 143: 506 – 513. https://doi.org/10.1016/j.proeng.2016. 06.064.

Parente, M., Cortez, P. and Gomes Correia, A. (2015). An evolutionary multi-objective optimization system for earthworks. *Expert Systems with Applications*, 42 (19): 6674–6685. http://doi.org/10.1016/j.eswa.2015.04.051.

Parente, M., Gomes Correia, A., Figueira, G. and Mehrsai, A. (2018). Towards improving earthworks production from an Industry 4.0 perspective: the role of remote information technologies and dynamic optimization techniques. *Proceedings of 7th Transport Research Arena (TRA 2018)*, Vienna, Austria.

Parente, M., Amândio, A., Moutinho, J. and Gomes Correia, A. (2022). Digital twin optimization framework for earthworks production optimization and management. *Proceedings of the 11th International Conference on the Bearing Capacity of Roads, Railways and Airfields* (BCRRA2022), Trondheim, Norway.

Paulmichl, I. Adam, C. and Adam, D. (2022). A numerical study on the response of the oscillation roller-Soil interaction system. *Advanced Structured Materials*, 156, pp. 161 - 172, http://doi.org/10.1007/978-3-030-79325-8_14).

Rastogi, E., Kumar Maheshwari, M., Roy, A., Saxena, N. and Ryeol Shin, D. (2022). Energy efficiency analysis of narrowband Internet of Things with auxiliary active cycles for small data transmission. *Trans Emerging Tel Tech*., 33(1):e4376. https://doi.org/ 10.1002/ett.4376.

Raza, U., Kulkarni, P. and Sooriyabandara, M. (2017). Low power wide area networks: An overview. *IEEE Communications Surveys & Tutorials*, 19 (2): 855-873, https://doi.org/10.1109/COMST.2017. 2652320.

Shanmuga Sundaram, J. P., Du, W. and Z. Zhao (2020). A survey on LoRa networking: Research problems, current solutions, and open issues. *IEEE Communications Surveys & Tutorials*, 22 (1): 371-388, doi: 10.1109/COMST.2019.2949598.

Singh, R. and Tyagi, V. (2023). Innovative applications of IoT in civil engineering: Enhancing efficiency and sustainability. *3rd International Conference on Advancement in Electronics and Communication Engineering,* AECE 2023: 1028 – 1031. https://doi.org/10.1109/AECE59614. 2023.10428145.

Taddeo, M., and Floridi, L. (2018). How AI can be a force for good. *Science*, 361(6404): 751-752. https://doi.org/ 10.1126/science.aat59.

Tan, J., Sha, X., Lu, T. and Dai, B. (2022). A short survey on future research of AI and IoT technologies. *2022 International Wireless Communications and Mobile Computing*, IWCMC 2022: 190 – 195. http://doi.org/10.1109/ IWCMC55113.2022.9825425.

Tatsuoka, F. and Gomes Correia, A. (2018). Importance of controlling the degree of saturation in soil compaction linked to soil structure design. *Transportation Geotechnics*, 17(Part B): 3-23. https://doi.org/10.1016/ j.trgeo.2018.06.004.

Xu, G., Chang, G.K., Wang, D., Correia A.G. and Nazarian, S. (2022). The pioneer of intelligent construction—An overview of the development of intelligent compaction. *Journal of Road Engineering*, 2 (4): 348 – 356. https://doi.org/10.1016/j.jreng.2022.12.001.

Zhang, W., Pradhan, B., Stuyts, B. and Xu, C. (2023). Application of artificial intelligence in geotechnical and geohazard investigations. *Geological Journal*, 58 (6): 2187 – 2194. https://doi.org/10.1002/gj.4779.