Automation in Construction 131 (2021) 103918

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Low-cost internet of things (IoT) for monitoring and optimising mining small-scale trucks and surface mining shovels

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ARTICLE INFO

Keywords:
Internet of things (IoT)
Fleet information system (FIS)
Fleet management systems (FMS)
Mining equipment
Material handling

ABSTRACT

This paper discusses the design and deployment of low-cost Internet of Things (IoT) in medium-scale open pit mines to optimise the performance of their mining small-scale trucks and surface mining shovels. Low-cost IoT can be implemented in medium-scale operations to automate the collection of process management information that is currently measured manually, replicating part of the results delivered by commercial Fleet Management Systems (FMSs) such as the calculations of the number of truck cycles per shift, the shovel loading time, truck and shovel positioning, tonnes moved per day, truck speed and average fleet efficiency. The process of developing mining benches can also be monitored.

By monitoring these tasks, FMSs in the mining industry allow mine operators to maximise productivity, reduce the number of equipment required to accomplish production targets, minimise material re-handling, supply the plant as planned and meet ore blending objectives for better metallurgical recoveries. In the case of large-scale mines, these mining operations are prepared to invest in the high cost of a typical FMS (of the order of $100,000/month depending on fleet size) because they enable mine operators to ensure that their capital-intensive fleets operate at peak productivity, generating maximum return on investment. By contrast, many medium-scale mines cannot afford the installation and ongoing costs associated with a commercial FMS. Medium-scale mines typically have low capitalization, rented mining fleet and are run on a day-to-day basis, with staff being employed or laid off on an almost continuous basis.

The emergence of low-cost IoT promises widespread and access to sensors and data that can be used for operational decision-making. This paper presents a trial of a low-cost, under $100, IoT-based Fleet Information System (FIS). The system does not attempt to replicate the functionality of a full FMS but delivers key management information to the mine operators while having low capital and running costs and no requirement for IT or technical skills for installation or maintenance.

In a test case in Chile, the FIS was used to inform operational management changes that resulted in a reduction of loading time, optimisation of mining truck routes and truck speed control for better safety without an increase in the mining cost.

The low cost of the solution allows medium-scale mines access to tools that can enable them to mirror the performance improvements of their bigger competitors. For medium-scale mines, that means longer life-of-mine, more local employment and a longer positive impact in the community.

1. Introduction

Mining companies in competitive markets are “price-takers”: the price for their product is determined by trading exchanges and control of supply is largely out of the hands of individual companies. To maximise their benefits, mines must reduce their average cost to increase the profit from fixed prices. To survive market fluctuations, miners are always obligated to control and reduce their average cost [1].

The steps of the mining value chain are to discover, establish, exploit, beneficiate, sell and reclaim [2]. Here we are concerned only with exploitation, which comprises the processes of drilling, blasting, loading and hauling, underpinned by the support functions of mining services and maintenance. Fig. 1 illustrates the operational mining tasks and how they interact.

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https://doi.org/10.1016/j.autcon.2021.103918
Received 10 June 2019; Received in revised form 7 October 2020; Accepted 18 July 2021
Available online 27 August 2021

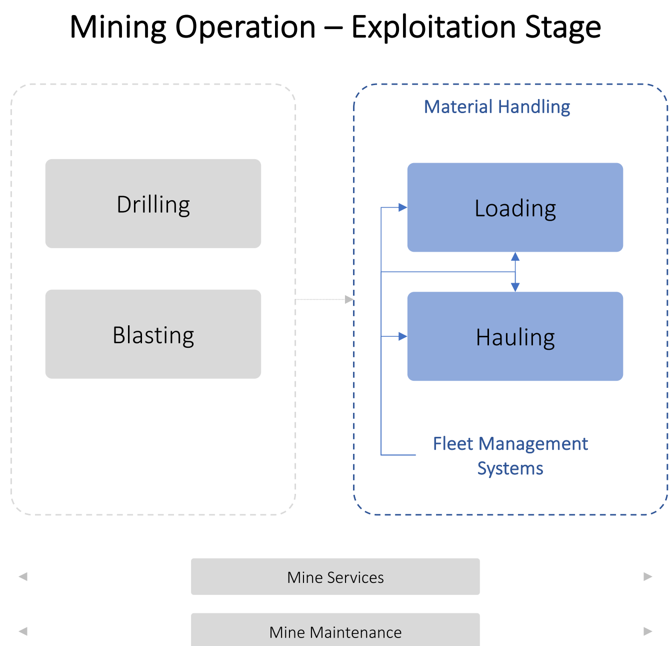

Fig. 1. Operation mining tasks. The figure represents the main tasks undertaken at mine site for producing mineral and transporting it to mineral processing plants.

The mining cost is made up of the expenditure on each of the processes illustrated in Fig. 1. In open pit mines, the loading and hauling process (also called material handling) is the dominant contributor, typically representing 50% of the mining cost [3–5].

Around the world, material handling in open pit mines consists mainly of truck-shovel based systems due to their high efficiency compared to alternatives [6]. This paper focusses on optimising the performance of truck-shovel systems, measured in tonnes per day, cycle and loading times, to lower the material handling and therefore the mining cost.

In many large-scale mines around the world, load and haul has been controlled through computer-based dispatching software since the 1980s [7]. Fleet Management Systems (FMSs) have been designed to maximise productivity or reduce equipment requirements to accomplish production targets, minimise re-handling, ensure supply to the plant and meet the blending objectives (where different grades of ore are mixed to aid metal recoveries in the mineral processing plants) [8].

An FMS typically uses design information, real-time data and user inputs to determine where ore and waste are available, and to send messages to trucks informing the driver of the next destination. Routes are calculated according to best fit priorities that are defined by the user [9]. FMSs can also assist decision-making through monitoring and compiling production statistics and suggesting equipment allocation.

The desired result is improved Overall Equipment Effectiveness (OEE), which links availability, performance and quality to measure equipment effectiveness [10]. An increase in the OEE has been proven to have a direct correlation with increased productivity and enhanced total production [11]. An FMS lets control room operators make decisions dynamically and respond to conditions by improving equipment availability, changing routing, making changes to haul roads or adjusting mining geometry [3].

FMSs have become indispensable tools for larger mining companies due to their demonstrated impacts on truck haulage requirements and reduced total cost, valued between 5% and 35% depending on operation [12]. Today, FMSs are widely considered as intelligent mining applications [13], because they enable business results to be improved through data-driven decisions.

This paper describes a case study in Chile. In Chile mining operations are divided into three classes: large-, medium- and small-scale, where each class is defined by its production levels. Small-scale mines are defined by law [14] as producing less than 5000 t of ore per month. Large-scale mines are defined by law as producing more than 75,000 t of fine copper [15]. Therefore, medium-scale mines are those mines in between, and the case study is on such a medium-scale mine.

Internationally and in Chile the focus of FMSs has been in large-scale mines: there is large capital deployed and ensuring its effective use by increasing the scale of production is essential. However, FMSs have high capital and running costs and significant non-mining technical skills are needed to install and maintain them.

Most of medium-scale operations fall short of capital, operating budget or the IT-related skills to implement and maintain a commercial FMS. At the same time, medium-scale operations are subject to the same cost drivers as large operations – as mentioned earlier load and haul typically contributes about 50% of operating cost. Poor technology implementation in small- and medium-scale manufacturing enterprises is a world-wide concern that goes beyond mining. In many industrial sectors, only a few companies have the necessary capital to implement advanced manufacturing tools and techniques that are heavily based on computing [16] [17].

Over the last two decades there has been a growing movement to add intelligence to everything, to develop the Internet of Things (IoT), also called intelligent manufacturing or Industry 4.0 [16]. These techniques can open a new era, measuring product performance and autonomously managing product service needs [18]. They can also potentially open up technology to smaller companies by reducing the capital cost and the in-house computing skills needed for implementation and maintenance.

This paper presents a low-cost IoT design and implementation of a Fleet Information System (FIS) for medium-scale mines, to retrieve and process data for optimising loading and haulage processes, at an open pit mine in Chile. By doing so, we show that medium-scale operations can improve some of their load and haul management by reporting parameters such as the number of truck cycles per day, the average loading time, truck and shovel positioning, tonnes per day, truck speed control, average fleet efficiency and benches developing. These parameters are currently measured manually or nor at all. The FIS generates some of the key reports that an FMS would provide at a much lower capital and running cost.

The mining market is driven entirely by commodity prices therefore any improvement in efficiency impacting the cost not only expands profits, it also enables to the operations to continue operating when the commodity prices are lower, sustaining employment.

In this paper, Section 2 reviews the literature on different commercial fleet management options in mining operations and introduces the concept of low-cost Internet of Things. Section 3 presents the case study, describing the mine site and the low-cost IoT system that was designed and installed at the site. Section 4 presents the results from the case study, which are discussed in Section 5. The final section contains the conclusions and recommendations from the study.

2. Background

2.1. Fleet management systems

Allocating shovels and trucks in an open pit is a dynamic process: there are many scenarios with a large variety of shovel locations and truck destinations. FMSs have emerged to deal with this optimisation problem by considering three main steps: selecting shovel locations, solving network problems by estimating truck and shovel waiting times, and finally dispatching every truck by solving an assignment problem [19]. These operation tasks can be optimised using FMSs [6].

The algorithms and software in FMSs that are already applied in industry rely on robust dedicated mine system management hardware, with high capital cost. The systems include central computer units with one or more individual computers, databases in communication with the central computer (usually configured in SQL), servers and replication servers. The central computer system uses wireless transceivers to connect to mobile computers that are attached directly to the various pieces of mining equipment. A messaging system is always incorporated to ease the generation of human-data inputs [20,21]. Additionally, large systems may be managed from remote locations such as remote operations centres that do not have continuous communications with all trucks and shovels because of restrictions on the wireless network in many mining pits.

A typical FMS [4] consists of communications infrastructure and central computer systems which communicate to truck, shovel and ancillary field systems [21–24]:

1. The central computer systems are typically incorporated into a mining company's IT system;
2. The truck, shovel and ancillary field systems collect GPS position [21] as well as equipment status and performance data. This information is then communicated over a wireless communications system. The mobile field systems are coupled into the trucks and shovels to monitor parameters such as engine speed and drill operation. The vehicle systems can often be interrogated and updated via a user interface in the equipment [25];
3. The communications infrastructure depends on location, and can include WiFi [26], wireless mesh networks [27], mobile telecommunication standards such as LTE [28] or 5G [29] and the emerging Low-power Radio standard (LoRa) [30,31].

All the three elements lead to expense:

1. The computer system and control room are on the mine premises, which require technical support staff and have the costs associated with reliable, well-supported computer servers;
2. The ancillary systems are installed in equipment and must be engineered to a high standard because they interface with the vehicle systems. Therefore, this requires the trucks and shovels to be taken off production while the system is installed or maintained;
3. Wireless coverage is always a challenge because of the topography introduced by the mining excavation. It is unusual for all locations of the mine to be within line-of-sight of a single location, and underground mines require numerous access points and/or leaky feeder, both with cost implications.

The medium-scale sector of open pit mines is radically different to large-scale mines. Today (2020), these mines communicate source and destination allocations to trucks through manual dispatch via two-way radios. Managers typically organise fleet equipment by assigning fixed allocations to shovels and trucks at the beginning of the shift. This static management of the fleet makes changes during the shift difficult to implement. In the trade-off between static management and the installation of an FMS, the high cost of the FMS trumps the disadvantages of static management.

Although FMSs have steadily evolved over the years, they have been slow entering businesses with smaller profits, lower capacity equipment and less infrastructure in the form of few mining routes or small equipment fleet, where an optimisation algorithm for dispatching trucks to shovels is not necessarily needed. However, a system to monitor the mining fleet's downtime losses is fundamental to ensure that the planned scheduled is maintained.

2.2. Internet of things

In this paper, Internet of Things (IoT) is used as an enabler of a new sort of business. It has been applied to build a platform that assists medium-scale mines in monitoring and controlling production.

Minerva et al. [32] presents a number of definitions of the Internet of Things, including: from the IEEE: "*A network of items – each embedded with sensors – which are connected to the Internet*"; from the ITU: "*ubiquitous network*"; and they go on to endorse the definition "*Available anywhere, anytime, by anything and anyone.*"

From a business point of view, Haller et al. from SAP define the IoT [33] as "*A world where physical objects are seamlessly integrated into the information network, and where the physical objects can become active participants in business processes. Services are available to interact with these 'smart objects' over the Internet, query and change their state and any information associated with them, taking into account security and privacy issues.*" This is a good description of a modern FMS, except that FMSs are often implemented over proprietary communication systems, rather than the internet.

IoT facilitates the visualization of information that was previously inaccessible, helping systems to interchange data and bringing the physical and information world together to make decentralized decisions [34].

IoT as a crucial element of the Industry 4.0 is based on the concept of a Cyber Physical System (CPS) [35] (Fig. 2), where Connected Devices, Cloud Storage Systems (CSS) and Application Systems (AP) are combined to implement a smart manufacturing process [36]. In this paper, the broad architecture of CPS's has been used to design and implement the FIS.

IoT results in the extension of current network connectivity, combined with sensor-device abilities that cannot be called simple computers [37]. Each part, sensor or actuator taking part in the network is capable of perceiving the environment or machine conditions, for instance thermal, mechanical, optical, electrical, acoustic and displacement signals [38] and subsequently reporting those states to the Cloud Storage System, using the internet as a communications medium. The connection generates a self-guided and dynamic value-added interconnection across the value chain [39]. Additionally, IoT enables the possibility to submit information automatically without human-human or human-computer intervention [40].

IoT applications in industrial environments have grown rapidly in recent years, leading to the concepts of smart farming, transport, health, infrastructure management [41] and mining [42]. The agriculture industry has adopted IoT technology widely to improve production, commerce and transportation due to the need of air, soil, water, plant and animal monitoring [43]. The transportation sector has applied IoT for predictive maintenance and to improve the availability of equipment [41]. Industrial machine operators embrace IoT to control quality, lower cost and improve the manufacturing process [44]. The mining industry has also applied IoT for reducing accidents (collision and proximity avoidance) and improving safety [42].

Web or cloud-based technologies enable rapid updates to applications and friendly adaptable features that provide new approaches increasing further adoption, because IoT applications served over the web do not require the customer to employ a specialised IT workforce to maintain them.

The application described here has many similarities with these other applications, including low cost and server-based services, but this is the first time that IoT technologies have been applied directly to the management of load and haul equipment on medium-sale mines. When all the properties of connected devices, cloud storage and application systems are available, the idea of providing much of the management information delivered by commercial FMSs is achievable using a number of "things", many on trucks, and the internet, hosting FMS applications. By using low cost "things", spreading the computing infrastructure cost over several users and providing a user-friendly web-based, device-neutral interface, it is possible to bridge the gap in fleet management capability between large- and medium-scale mines.

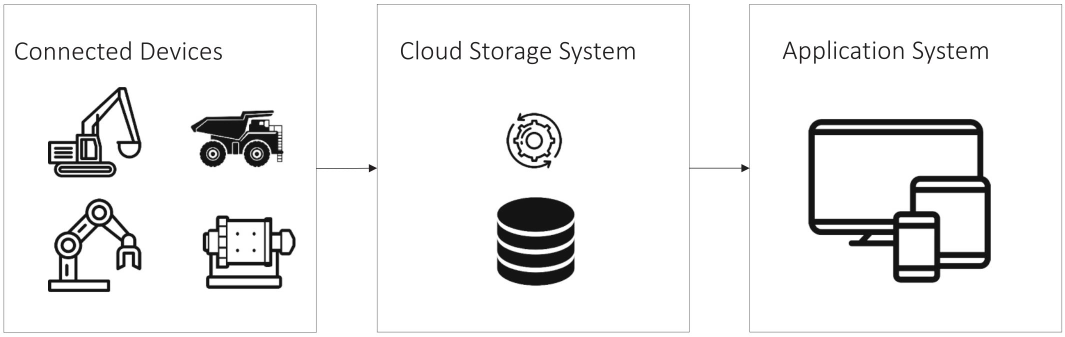

Fig. 2. Cyber physical system.

3. Methods

3.1. Device design and network

The absence of IT infrastructure in medium-scale mines can be compensated for by implementing low-cost IoT sensors sending data to a server in the cloud, providing the data that is available in other industries or even used in large-scale mines via a web interface on any internet-connected device.

The low-cost IoT sensor and data processing package described in this paper incorporates technology to monitor production and predict process patterns, imitating some key information outputs used regularly in commercial mining FMSs such as the calculations of the number of truck cycles per shift, the shovel loading time, truck and shovel positioning, tonnes moved per day, truck speed and average fleet efficiency. The main goal is to build a digital platform constructed on the basis of machinery and equipment identification, to visualize the production processes and their results.

The CPS concept proposes three main blocks: Connected Devices at the mine site, Cloud Storage Systems that receive and store data and an Application System, where a new user experience is provided using web browser tools [35]. The case study system has been implemented using the same architecture.

The system architecture is illustrated in Fig. 3. Single-board computers (SBCs) are installed in the trucks, while each shovel has a Bluetooth beacon installed. Data from the SBCs is transmitted via the internet to a cloud storage system, from where management information is generated for users, who access that information via a web browser. The sensor package implemented in the case study consists of a Raspberry Pi Single Board Computer (SBC) with an attached Mobile Broadband Modem (MBM) and Global Navigation Satellite System (GNSS) module.

The shovel is fitted with a Bluetooth-based radio frequency beacon in its window to notify the truck when it is adjacent to the shovel, and to allow the truck to time its interaction with the shovel, providing shovel cycle time. The beacons are Estimote proximity beacons, using Bluetooth Low Energy technology that should run for three years on a CR2477 battery [45]. Beacons are also installed at places of interest such as the dumping points. Fig. 3 illustrates the system connections.

Commercial FMSs include touchscreens and require operators to input some events such as arrival at the loading point, route conditions, or changes in operational status if the system cannot identify the situation by itself. The problem in these cases is the operator's motivation and willingness to do so. The system developed in this paper is deliberately designed without any interface in the cabins of the trucks and shovels. The system establishes what task is being performed by the trucks from their position and interaction with the Bluetooth beacons in the shovels.

Every SBC is designed to acquire and submit data to a cloud storage system once powered, with no calibrations or test periods. It can be

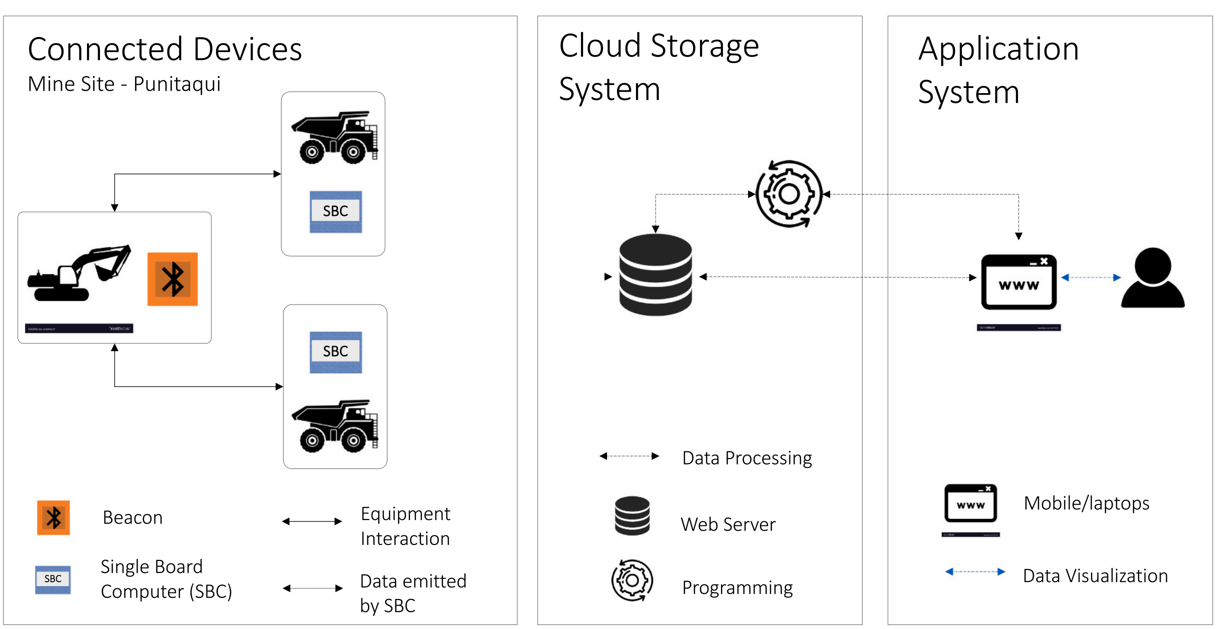

Fig. 3. System configuration and device interaction based on a Cyber Physical Systems (CPS) architecture.

installed by an unskilled person in minutes and does not require a major stoppage such as an equipment maintenance overhaul for installation, in contrast to the FMS equipment installed on trucks at large-scale mines. The SBC represents the most important system component, due to its capacity to interface with different sensors through its USB, I2C and SPI ports, as well as its ability to read, store and submit data from its Global Navigation Satellite System (GNSS) module and Bluetooth module when it establishes communication with the beacons on the shovels.

3.2. Server-side systems

Haller et al.'s definition of the Internet of Things [33], discussed earlier, starts with "*A world where physical objects are seamlessly integrated into the information network*". In this case, the physical objects (trucks) are integrated into the information network through their data connections to the internet, but it is the server side that gives the system its utility.

The application described here uses Google Cloud Platform to store data and calculate indicators, specifically, the Google IT Core and PubSub modules [46]. The SBC subscribes to PubSub over HTTPS as a publisher. Alongside this platform, FireStore is used as a data repository. The application is managed using ReactJS via the web, and development is undertaken using JavaScript and NodeJS, which is Google Firebase's default engine. This approach is known as "serverless", in which a service provider, Google in this case, is paid on the basis of data consumed and carries no capital cost for the user. [47]. A typical server running on the Google Cloud Platform would cost in the region of $100/month for sufficient compute and storage resources to deliver this application.

3.3. Connected devices at mine site

The SBC consists of multiple devices as illustrated in Fig. 4:

- Micro-controller: a small Raspberry Pi dual core computer with 1 GB of RAM running the Linux operating system on single printed circuit board, together with program and data memory and peripherals;
- A u-blox NEO6M-based GNSS (Global Navigation Satellite System) receiver that generates data encoding geographical position, speed and altitude in UTC format.
- Bluetooth: (BT) Bluetooth 4.1 (2.4 GHz) receptor module for receiving the beacons' Bluetooth signals, allocated on shovels;
- Mobile Broadband Modem (MBM): communication module for sending and receiving data from the SBC to the Cloud Storage System. The system works on 2G and 3G signals. There is mobile data coverage across the mine site.

The SBC is installed in the truck by mounting it using Velcro strips in a location where its GNSS receiver has visibility of the sky, such as on top of the dashboard. The only connection between the SBC and the truck is the 12 V power connection that goes from the SBC to the cigarette lighter socket in the truck.

The beacon, also included in Fig. 4, is a simple device designed to repeatedly transmit a wireless identifier using the Bluetooth low energy protocol, at a repeat-rate defined by the user. By experiment, it was determined that the Estimote beacon used is typically detected when the truck is within 5 m from the beacon. The beacon is enclosed in a waterproof container and attached to the shovel or other machinery using Velcro.

Loading time is one of the key metrics that is diagnostic of the efficiency of the load-haul operation. Long loading times indicate potential problems with the shovel or truck location, or with the state of the rock being moved, while short loading times might indicate that trucks are not being loaded to capacity. The SBC is able to determine the loading time by identifying the first point of contact with the beacon's Bluetooth signal and the signal loss as the truck drives away. If multiple signal losses and recoveries happen during the loading process, the system can recognise the first and the last contact, assigning a time to the load.

When the truck identifies the shovel, its SBC also captures its own GNSS data: latitude, longitude, altitude and speed. The data is stored in a temporary local database on the SBC and is transmitted to the CSS when mobile signal is available. Once data is confirmed as received by the CSS, it is deleted from the SBC database.

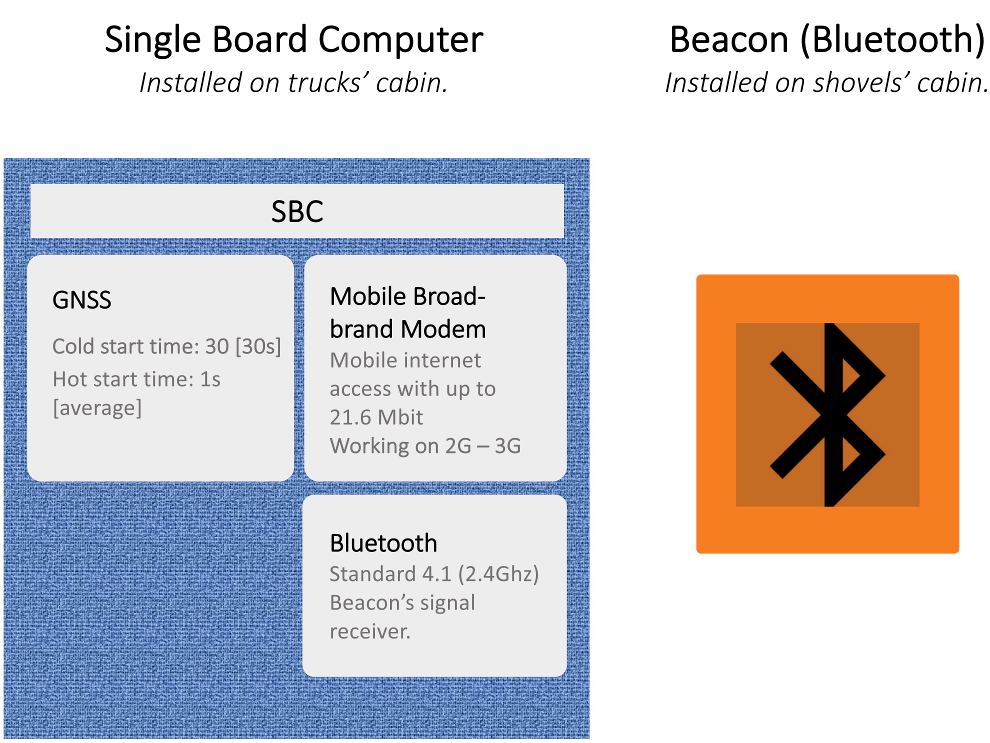

Fig. 4. Raspberry Pi single computer board and beacon.

3.4. Cloud storage system

The Cloud Storage System is a remote server system whose most important functions are to receive, store and process data captured from the mine site environment.

The data package collected by connected devices is transmitted every 30 s through the local mobile network to the CSS. A 30-s cycle time was selected because it provides adequate sampling of the time taken for a shovel to load a truck which is typically several minutes, while minimizing the cost to transmit mobile data. Table 1 summarises the data fields transmitted by the SBC when it relays its position from its GNSS. Table 2 summarises the data fields transmitted when the SBC interacts with a beacon.

3.5. Application systems

To obtain an economic benefit from the system, it is necessary that the mining personnel access the data quickly and intuitively. A web-based platform has been built to manage the data as soon as the information is received, every 30 s.

Data from the trucks is automatically stored in an SQL database on the CSS as it arrives. Queries are then run on the database by the Application System to extract measurements of interest.

A real-time map is programmed to display coordinates in real time, depicting mining equipment movements and performance. The users can make decisions based on their mining expertise, looking at the point concentration, colours, sizes and alerts on the real-time map. Fig. 5 and Fig. 6 show the user interface of the web-based platform.

The Applications System can be accessed through different devices connected to the internet without the need to install applications – everything runs on the browser on the user's device. Following consultation with end users, the dashboard design for users contains a main menu that offers two options: near real-time information (Fig. 5) for each truck monitored and reports such as heat maps or speed limit contraventions in a specific period of time selected by calendar (Fig. 6).

4. Case study

In order to assess the application of low-cost IoT for optimisation of haulage in medium-scale open pit mines a case study was undertaken in Chile. Altos de Punitaqui Mining Company (APMC) is a copper, gold and silver producer located in Region IV, northern Chile about 400 km north of Santiago (Fig. 7).

APMC is comprised of the Cinabrio and Milagro Underground Mines, the Fusionada Open Pit (Fusionada) and a flotation mineral processing plant. The mineral extracted reaches 3000 t/day. APMC's plant capacity is 4000 t/day, so to run at capacity it buys ore from nearby mines. APMC is an important economic development centre in the area, at a local and regional level.

Like most other mines with similar production levels, APMC is susceptible to fluctuations in the copper price, that can result in closures for a period of months or even years [48–50]. Controlling the mining cost and targeting the production objectives is essential to maintain profitability in times of low price. However, at present, critical parameters such as truck utilization cannot be monitored efficiently due to budget constraints and the high cost of typical fleet management systems.

Table 1
Raw data collected.

	Item	Description
1	Timestamp	Date and time in utc (time zone 0)
2	Asset	The asset that sends the data (truck).
3	Checkpoint	Gantry or event control point (shovel)
4	Type	Type of event
5	Latitude	Geographical position
6	Longitude	Geographical position
7	Altitude	Geographical height
8	Speed	Instantaneous speed

Table 2
Registered event types.

	Type of event	Description
1	Location	Asset update every 30 s
2	checkpointInit	Entry to a control point (shovel)
3	checkpointUpdate	Remains in a control point (shovel)
4	checkpointEnd	Output from a control point (shovel)

Fusionada mine (Fig. 7) utilises a truck and shovel system for its material handling process. The equipment selection (type of trucks or shovels and their capacities) was determined by long-term mine planning. The long-term plan considers parameters such as truck trip cycle times, loading times, trucks and shovels' overall performances, destinations of ore and waste tonnage, operational cost and mine uncertainties [51]. These variables, that are linked to the volatility in the commodity market, have a direct impact on the material handling optimization and mining cost reduction.

Fusionada's current fleet consists of two Komatsu 450 mining excavators (bucket capacity: 5 t), eight Mercedes Benz Actros 3336 mining trucks (load capacity: 20 t), one grader, one water truck and one bulldozer. The Mercedes Benz Actros 3336's is not dedicated mining trucks, but on-highway trucks being used in a mining role.

The Komatsu 450 mining excavator was selected because it provides versatility compared with the larger hydraulic and rope shovels typically used in large-scale mines. Its travelling speed of 5.5 km/h gives it the ability to move from one loading point to another in a short time, allowing the excavator to be allocated to more than one loading position in a single shift, something that is unachievable with larger, slower equipment. However, the reliance on only two shovels is a significant risk, so monitoring the equipment and undertaking planned maintenance is fundamental to reduce breakdowns and is critical to the overall efficiency of the haulage process [52].

FMSs from original equipment manufacturers are typically not able to work with equipment from other manufacturers. The mix of Komatsu mining excavators and non-mining trucks means that an existing FMS offered by Komatsu, Caterpillar or Sandvik would have to be adapted to function properly. A mixed fleet of equipment from different suppliers and equipment that may or may not be purpose-built for mining is common on small and medium mines. Thus, a more flexible solution is proposed to integrate with equipment from several manufacturers.

Due to the scale of Fusionada and budgetary constraints no affordable FMS for monitoring its exploitation stage was available. Additionally, despite having highly skilled mining personnel, there is no spare capacity or competence to develop technology in-house for monitoring and establishing production patterns for cost reduction or productivity improvements.

At the time of the test deployment, Fusionada had three production benches where material is being loaded, illustrated in Fig. 8. The shovels distribute their time during the shift or the week to cover these 3 benches. A "bench" is ledge that forms a single level of operation above which mineral or waste materials are mined. The production benches are 393, 363, and 345. The geometry in an open pit depends on equipment size and each pit is designed and built to achieve the highest performance at a specific site. At Fusionada, the bench height is 6 m and the bench widths vary from 6 m to 8 m.

The Fusionada destinations are the ore stockpile close to the mineral processing plant and two dumpsites for waste rock. Fig. 9 illustrates the actual routes between production benches marked in pink, and the stockpile and dumpsites in marked in green and blue respectively. Note that one of the production benches, 393, is only producing waste material. The northern dumpsite is separated from the working benches by a steep slope, hence the long loop to reach it. Fig. 10 is a schematic of the mining equipment movements represented in Fig. 9, using the same

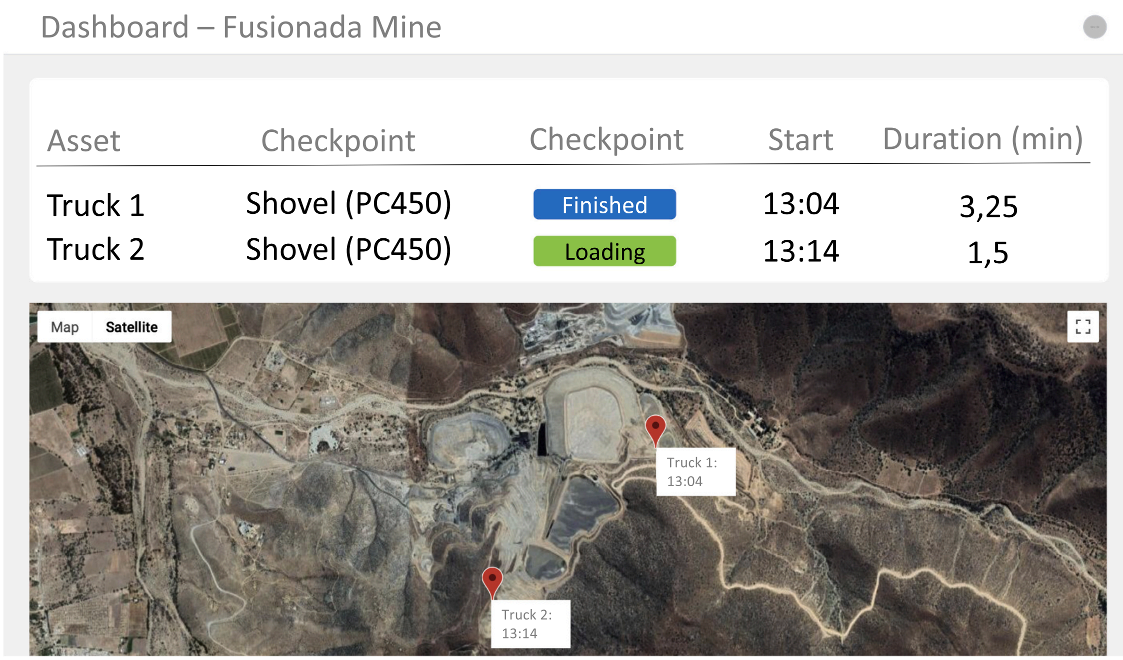

Fig. 5. A screenshot of the web-based platform for visualization. The Dashboard shows the truck position in real time, the interaction of each truck with a specific shovel, time of interaction, operational status (loading or not) and loading duration.

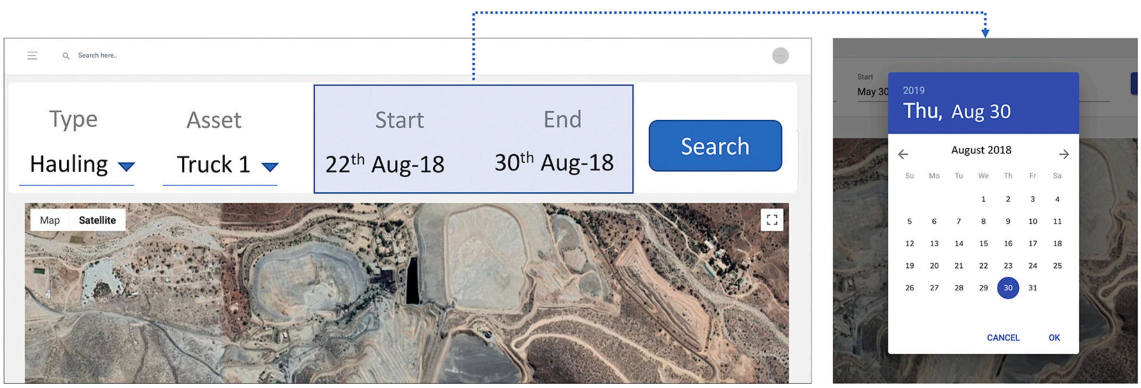

Fig. 6. A screenshot of the web-based platform for truck or shovel activity visualizations. Reports at a specific date.

Fig. 7. Location of APMC (left) and Google Maps satellite imagery of the Fusionada Open Pit (right).

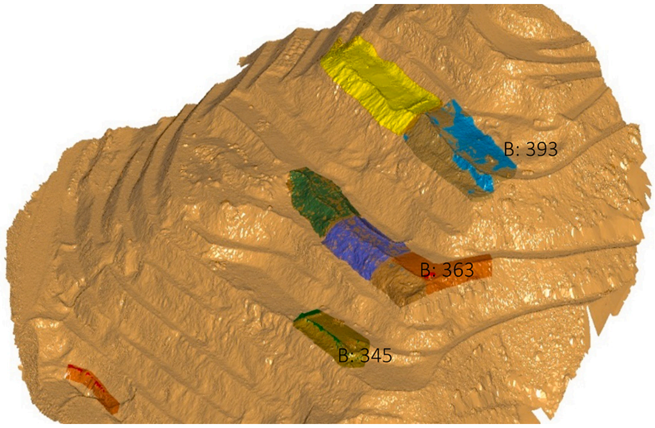

Fig. 8. Production benches at Fusionada Open Pit.

colours for an easy reference.

The ore and waste tonnage produced at Fusionada mine is reported at the end of shift. During the day, the ore tonnage is measured by a weight meter at the stockpile entrance.

In the case of waste, tonnage is not measured, it is assumed by considering the number of truck trips and a fixed tonnage per trip based on the capacity of the equipment, assuming 100% fill is achieved (20 t). Generally, the waste tonnage is reconciled at the end of every month by determining the actual tonnage by measuring the change in size of the waste dumps.

During the shift, there is no option to understand the production behaviour, recognise bottlenecks or their locations, identify equipment idle and lost time, improve productivity by changing assignments, or measure transportation route distances.

In respect of the loading process, there is no chance to control shovel saturation (where the shovel is at capacity and trucks begin to queue) or loading idle time. In many medium-scale mines globally, this is the reality: it is not possible to visualize mine production in real time, particularly when it is not possible to see the whole pit from a single physical location.

5. Results

The low-cost IoT FIS design was implemented in a trial for 14 days on 2 trucks, during which time the fleet moved approximately 80,000 t of ore and waste. The data retrieved directly from the trucks is their position and speed every 30 s, and whether the truck senses the presence of a nearby piece of mobile equipment by detecting its Bluetooth beacon.

Fig. 9. Mining route between production bench and stockpiles and dumpsites.

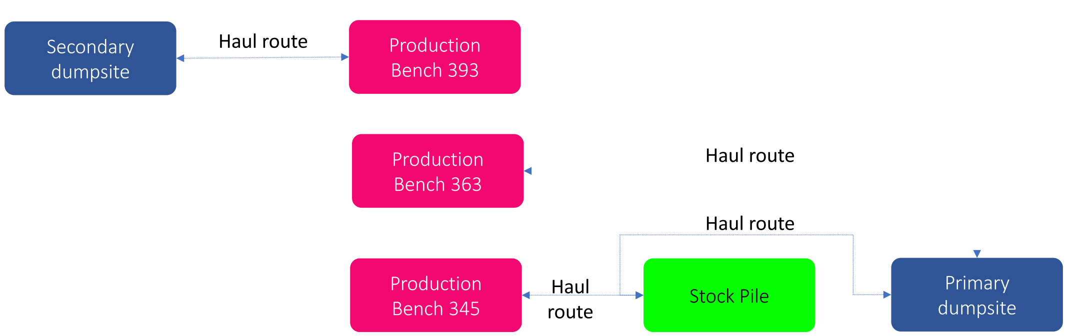

Fig. 10. Diagram of mining routes.

From the raw data, the following information can be calculated:

1. **Truck movements:** Truck position and speed are available every 30 s.
2. **Production:** Number of transportation trips, measured as the number of interactions between trucks and mobile plant during the shift.
3. **Mobile plant movements:** The shovel movements are slow, and their positions are determined every day at beginning of the shift. Their allocations can be corroborated with the positions detected by truck's SBC when it interacts with the shovel's beacons.
4. **Loading time**: Established by examining the time lapse between signal recognition and signal loss between the SBC and a beacon.

5.1. Truck movement

Truck movements can be analysed using the longitude, latitude, and altitude data acquired by the attached GNSS in the truck selected. Example data for a single day, for the truck APT001, is presented in Fig. 11. The data is plotted over a map or a satellite image of Fusionada to provide truck movement insights. The results are represented as a heat map: truck locations can be identified and the time spent at each location can be determined by associating the location with a colour: when the truck is standing or moving slowly, the colour is hot (red), otherwise it is cool (green).

Plotting the information in this way provides a methodology for analysing the operational characteristics of mining routes, truck speed in each route segment, and truck transportation mean distance. An analysis can then be undertaken to assess the design of the haul road routes and the location of pinch points and other obstructions to the trucks.

The movements of a second truck, APT002, are analysed in Fig. 12. The illustration indicates in red how the truck speed is reduced substantially in acute angle curves, impacting the overall productivity and hauling performance.

The slow-moving truck congestion shown in Fig. 12 (highlighted in the red circle) is a consequence of a period of bench development when the truck was forced to reverse up to the shovel prior to a loading area being established.

In Fig. 13, truck APT002 is dispatched to a waste dump following collection of rock from a shovel that was constructing a haul road during the test period. Due to the constrained loading configuration (the narrow haul road width and only limited options to build loading pads), the data shows that the processes of the road construction are slower and shovel cycle times are extended.

Utilising GNSS data from the truck, graphs can be plotted where the point size is a function of the speed, with larger points indicating a higher speed, as shown in Fig. 15. Filtering the data to one cycle is highly beneficial (Fig. 13, right), as it can illustrate the haul road performance and trucking capacity and show how the design of the haul road performs. The plot clearly indicates the number of times the trucks have to

Fig. 11. Heat map of GPS points to describe road usage intensity for truck APT001 during August 25th 2018. Hot colours indicate greater usage intensity or lower speed, and are symptomatic of curves or road conditions that may be improved.

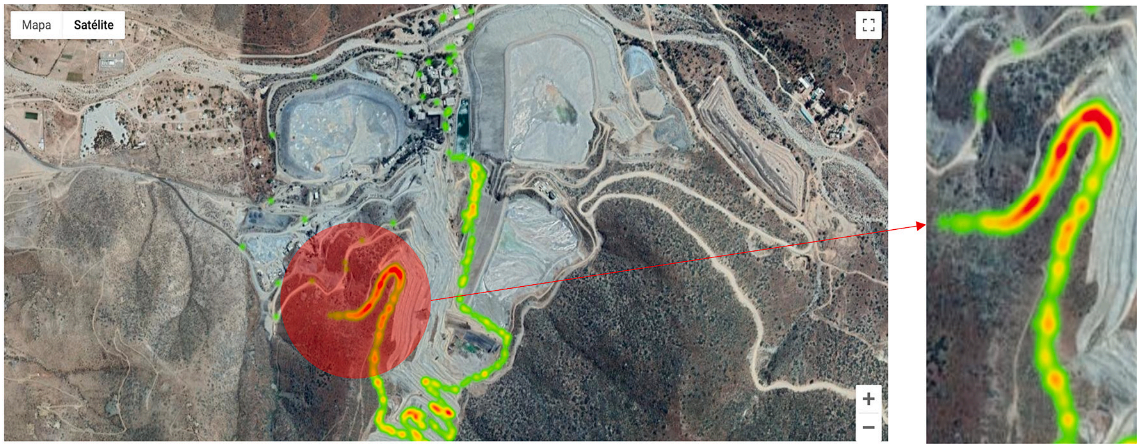

Fig. 12. Heat Map of GPS points. Red points indicate greater time spent at that location. In this case, the red colour is due to a new bench building (production area), where the truck moves backward, reducing speed and increasing the number of GPS points identified in the same area. - August 28th, 2018. The visualization allows to estimate productivity and building advance rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

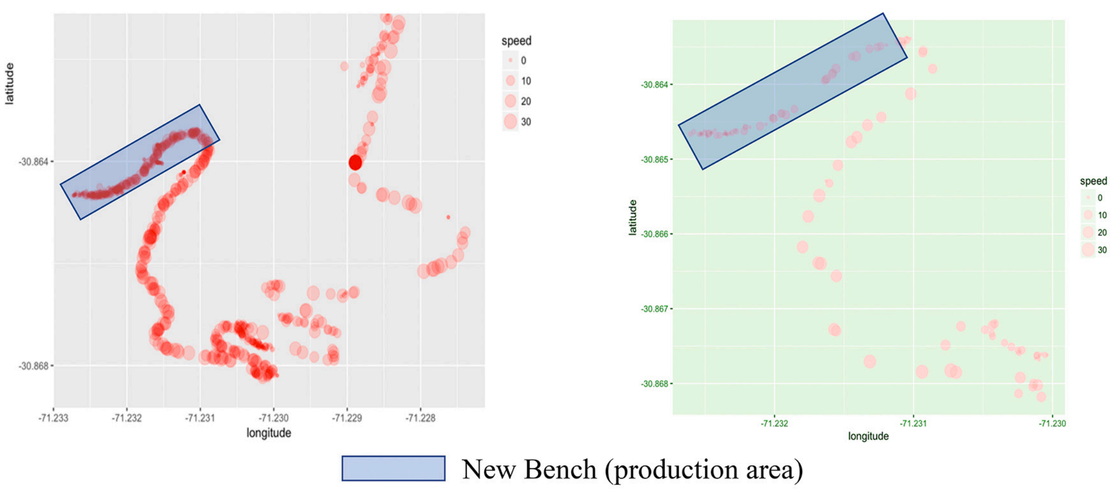

Fig. 13. Sizing points to measure instantaneous truck speed (in Km/h). The picture on the left shows overlapping points over a period of time specified by the user (for instance 2 h). The picture on the right filters one trip to observe the speed profile: speed on the new bench area is 0 to 10 km/h (small dots, top left). Once the truck leaves the new bench area, the speed rises up to 20 km/h (larger dots centre to bottom right).

slow down and return to maximum speed, and indicates poor passing design, overtrucking or potential driver training problems such as when a loaded truck is not given priority over a truck travelling empty.

The short-term mine planning in Fusionada is carried out based on the experience of the mine planners and information provided by equipment suppliers. Before this test, the mining department did not know the actual overall speed in tasks such as loading, hauling or building routes. This information can now be collected automatically and incorporated into future planning so that cost impacts can be measured or avoided.

The information is also useful in the short term for diagnosing problems with haul routes that can be corrected, improving fleet efficiency.

5.2. Production

Production is the key metric used by mining companies to manage their processes. It is one of the most important datasets required by mine operators from their FMSs. In a typical FMS installation, the dispatch engineer (the engineer who controls the fleet in a Dispatch room) controls every single lap during the shift in order to maximise production. The production measurements from the FMS are validated by the mineral processing plant and are taken as a reference number for mineral balance in the calculation of material balance at the end of the month.

Mine managers and superintendents are just as concerned about the number of truck trips per shift because they deliver a quick approximation for overall material movements and because the number of fleet effective hours can be estimated from this number. As well as being important metrics of productivity, these indicators are often the basis for productivity bonus allocations to the work force and must be accurate.

From the data collected by the FIS in this case study, the production for a single truck, measured in tonnes per day, can be counted as the number of interactions between the truck's SBC and the shovel's beacon. Each truck cycle can be timed from the first to last detection of the beacon indicating the shovel interaction and can be used to calculate the truck round trip time. Fig. 14 represents all trips undertaken by truck APT002 each day of the test.

Fig. 14 represents 9 days of normal production in August, followed by an interruption to the sequence on September 1st due to the nonavailability of the production drill rig needed for blasting.

Other cyclical variations in the recorded data shown in Fig. 14 are due to different allocations and distances between production benches

Day	Trips	Acum
22_Aug	8	8
23_Aug	27	35
24_Aug	19	54
25_Aug	12	66
26_Aug	10	76
27_Aug	36	112
28_Aug	24	136
29_Aug	10	146
30_Aug	18	164
1_Sep	1	165
11_Sep	8	173
12_Sep	14	187
13_Sep	9	196
14_Sep	5	201

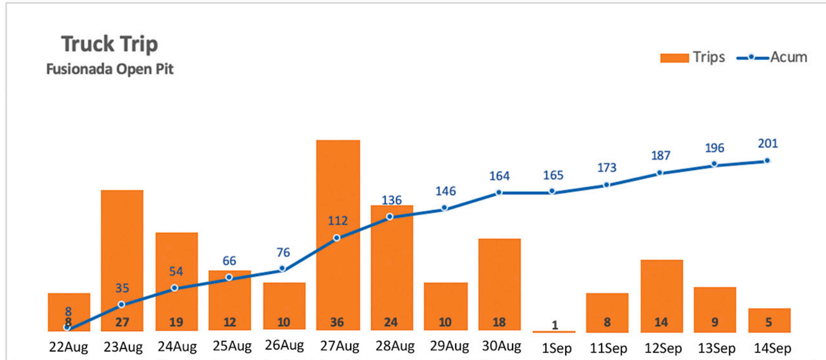

Fig. 14. Production trips for truck APT002.

and stockpiles or dumpsites. For example, the higher number of trips on the 27th August was due to short repetitive trips to the mineral processing plant from a nearby production bench.

This kind of information allows mining managers to take data-driven decisions such as prioritising production benches or distributing shovels in different allocations based in the lowest cycle or loading times in order to increasing production.

5.3. Shovel movements

Similar movement information to that from the trucks can be plotted and analysed for other mobile equipment. While shovels do not carry SBCs, every communication between a truck and shovel leaves a coordinate registration because the truck detects the shovel through its Bluetooth beacon, and it locates the shovel at that time through its GNSS. The shovel's location can then be determined, and its movements plotted.

The planned shovel positions during the test period are shown in Fig. 15 by the numbers 1–7 (over a 7-day period). These locations were allocated to ensure that the development of the bench occurs according to the mine plan. The data from the FIS can be used to calculate the actual establish bench advance rates and to determine if the shovel KPIs (Key Performance Indicators) have been achieved, by comparing how the measured movement of the shovel location compares to the planned movement.

For shovels, there will be a high density of points at each location where loading occurs because shovels will spend a lot of time at each location. The shovel daily advancement can be measured by following the path of the shovel over time, as illustrated in Fig. 16. A shovel advance of 20 m per day was measured using the system in this case.

Apart from location, the data also provides a measure of the loading time, from the length of time that a connection between the truck's SBC and the shovel's beacon is established. The loading time is an important variable to determine the match factor. The match factor is an indicator of the match between shovel size, truck size and truck haul distance and is used to determine whether the truck fleet has the correct number of trucks for the current operation. It is an important productivity performance and mine planning input for fleet equipment dimensioning [53].

The match factor compares the service time of the shovel to the cycle times of all the trucks. When the match factor is 1, the number of trucks is matched to the capacity of the shovel and neither trucks nor shovel wait. For match factors below 1, the shovel is waiting and the mine

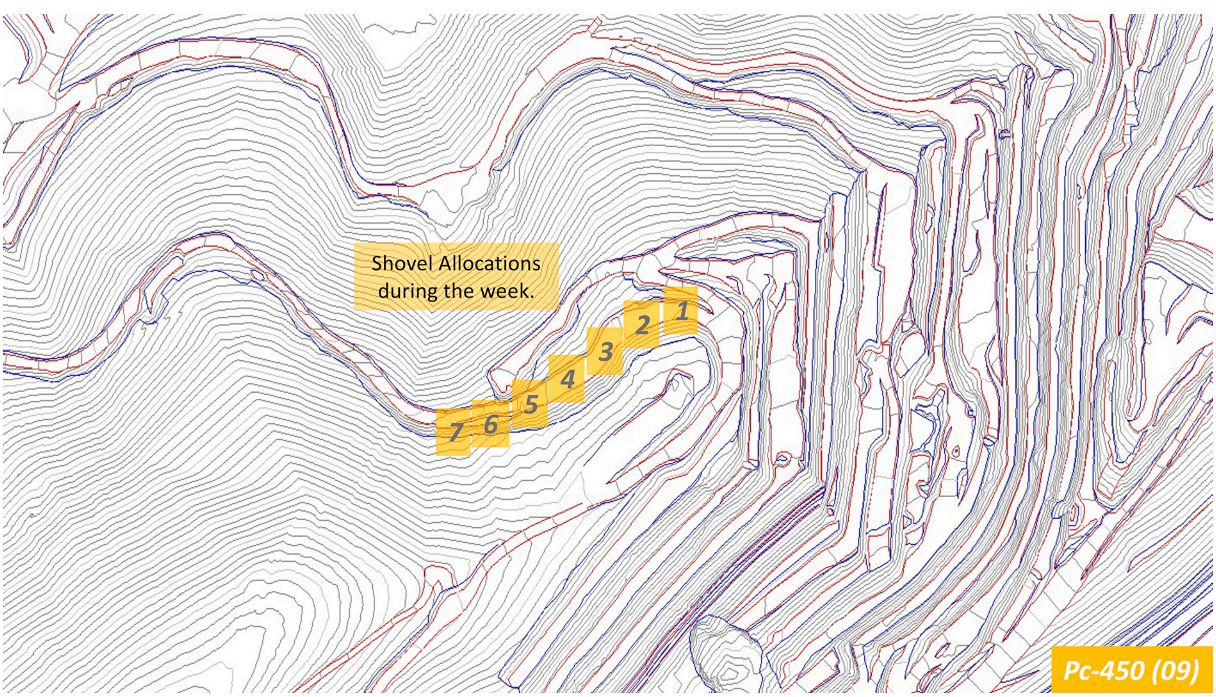

Fig. 15. Shovel allocation while building the new bench. The Short-term mine planning uses a square and a number to show the day of the week where the shovel should be placed in each location. (advance rate: 20 m per day).

Fig. 16. When loading, trucks are reading the beacon signals. Those beacon readings can be plotted over a map using the truck GPS location measured at the time. The points show where most loading ocurred during the bench development.

needs more trucks on that route. For match factors above 1, the trucks are waiting and the number of trucks on the route could potentially be reduced [54]. Matching trucks to shovels is a dynamic problem that changes with, among others, routes, rock properties, blasting quality and road gradient. Without measuring the loading time, a mine cannot optimise its fleet. An automated system allows measurement to occur continuously, potentially enabling continuous fleet planning and optimisation.

The FIS system described here and implemented in Fusionada Open Pit recognises loading time as those times of more than 0.75 min and less than 10 min. Less than 0.75 min clearly represents a system error such as truck passing a shovel without stopping to load and more than 10 min reflects an unusual loading condition where either the truck or the shovel experiences an operational issue.

Fig. 17 shows loading time for a single shovel over the period of the study. There is a downward trend in loading time. It is too early for the system to take credit for the improvement, it may just have been due to operators knowing that they were being monitored, a demonstration of the Hawthorne Effect [55], but the plot illustrates how FIS data can be used to manage fleet performance. The loading time demonstrates an improvement with time, from an average loading time of more than 5 min to less than 4 min and, more importantly, the variance has come down markedly. The reduction of 1 min per cycle can represent more than 3.3 effective hours over 2 weeks that can be recovered in this case study.

5.4. Safety

Because the information that is available in the database can be selected and filtered according to rules dedicated to analysing particular situations, safety applications can be developed using the same data. For example, amid the data generated by the GNSS is the instantaneous speed of each truck at 30 s intervals.

This indicator can help to determine compliance to safety regulations. The maximum speed can be measured in the application and compared with the speed limits at the mine site –usually 50 km/h on flat routes and 35 km/h on steep slopes. Data showing speeds over the maximums allowed on the mine is highlighted. Easy-to-analyse visuals can be generated to illustrate overspeed and take control actions, as illustrated in Fig. 18. In the figure, the positions where particular trucks exceeded the local speed limit are highlighted. The user can query by clicking on a hotspot to determine which truck was involved, as well as date and time.

6. Discussion

A low-cost IoT application, an FIS, was developed and applied with no major problems in the Fusionada Open Pit Mine to deliver some of the key management metrics that are also delivered by FMSs.

Data has been collected by the device described here and stored in a remote webserver. Subsequent analysis of the data collected confirmed that it matched the situation of the trucks on which the device was installed and is coherent with the real mining situation. During the proof of concept tests, the equipment was monitored continuously while the test was carried out and there were no information losses. The proof of concept also showed that the system can deliver data useful for management actions that could improve mine productivity or lower costs.

6.1. Installation cost reduction

Although infrastructure considered essential in commercial FMS implementations, such as a data-transmission system, computer networks, data centres and tools to test and support information technology were not installed, the system was capable of emitting essential

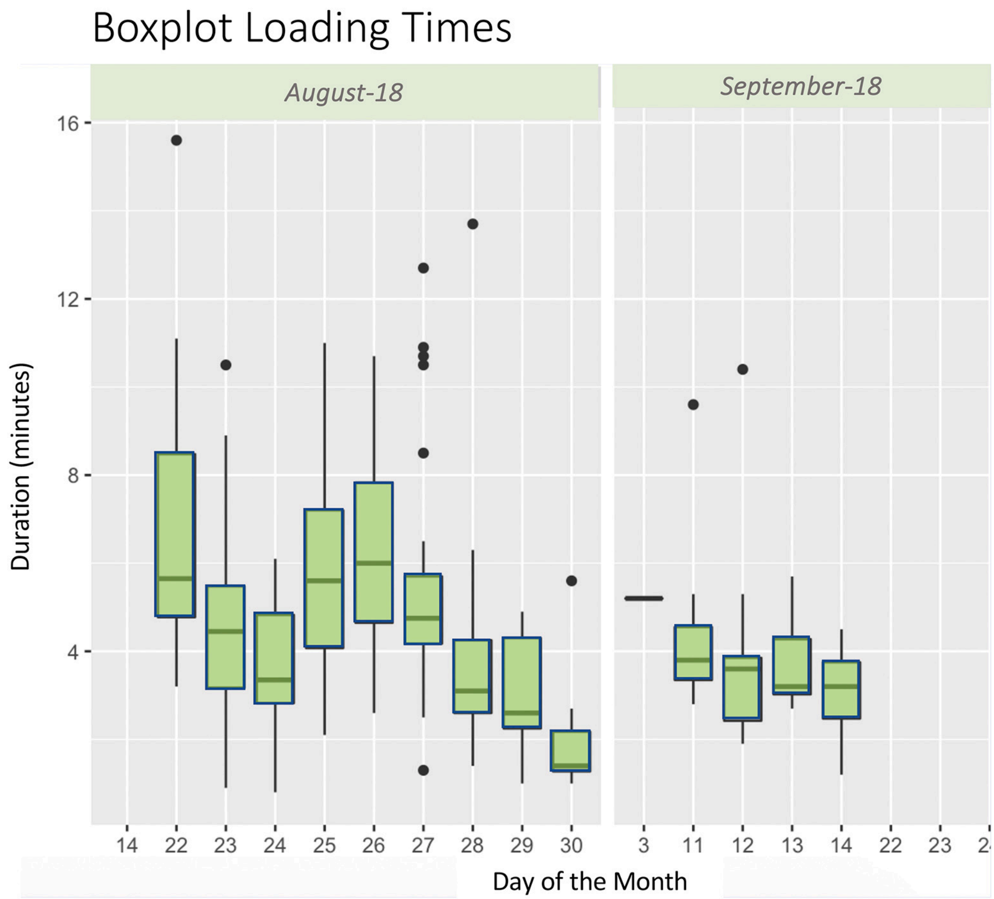

Fig. 17. Loading time measured per day in a boxplot. Loading improves from over 4 min to less than 4 min per load corresponding to approximately 1 min of improvement over the study period.

Fig. 18. Detection of truck speeds. The points shown over the map are points where trucks exceeded the 35 km/h limit. This sort of visualization helps to manage operator behaviour, avoiding accidents.

production data captured by the deployed devices. We have confirmed that equipment position and interaction can be monitored and recorded through sensors embedded in a low-cost IoT device ($100 hardware cost) that requires no hardware support from the truck in which it is mounted beyond access to power. The minimal interface between truck and device lowers the installation cost dramatically because it does not require skilled technicians and is quick enough that it does not require the truck to be removed from service for installation. In addition, there is no system calibration, source and destination definition, definition of data acquisition by sensors, or set up of interaction between devices. The system, which relies on mobile signals, works in real time with an easy connection to the webserver that stores and presents its data.

By comparison with an FMS, data centres and remote operation centres are not needed on the mine, as mobile phones or laptops already in use are sufficient for retrieving and deploying information for rapid decision-making.

6.2. User interface philosophy

On FMSs, an operator's touchscreen has become a universal tool which aims to eliminate information losses by allowing the operator to manually input data into the system. The touch screen demands the operator's attention and willingness while driving, to populate fundamental data required for the FMS algorithms to function correctly.

In this case study, the need for a touchscreen placed in the operator's cabin was deliberately removed from the conceptual design, to avoid the dependence on the operators and their motivation to provide data to the system. Removing the touch screen also enhances safety by removing a source of distraction for the driver.

All information about device interactions is determined in software by examining the relationships between different sources of data, particularly the GNSS and the presence of Bluetooth beacons.

6.3. Haulage transportation and traffic

The transportation distances and equipment allocations are easily identified from the GNSS data. Interpretation of the dataset provides a useful and powerful tool to mitigate against time losses and increase productivity. Information relating to delays, queue times, performance and truck speed can be monitored, and management actions can be taken to correct non-conformance to standards, and to improve the efficiency of the whole network.

6.4. Improving mining haul routes

Plots of the point concentration of GNSS data provide meaningful insights into truck performance. The user can easily determine the speed in each segment of the haulage road, to identify tight corners, unsuitable gradients or road surfaces requiring maintenance. With this information, it is easy to maintain or re-design mining routes to improve speed, performance, production and productivity, and to lower maintenance costs.

6.5. Technical skills shortage

There is an absence of IT skills on typical medium-sized mines. The FIS overcomes this lack through its ease of installation and hardware simplicity. In addition, knowledge about hardware configuration is not required for installing the system, and reporting is web-based, so the system does not require on-site IT expertise. In operation, the system does not demand high technical skills because mine staff do not interact with the system. Mine managers or operators review information online for managing the mine and do not require data processing skills to deploy and observe production patterns.

6.6. New tool development

Many new tools can be developed with the information acquired. Because the user-interface is delivered from a web service, the service provider can add typical FMS functionality such as ore blending control, queue control, speed profiles for trucks, allocation alerts, and bottle neck identification along the haul routes as they are requested by users. These upgrades can be added in small increments, as the managers using the tool become more comfortable and proficient with the system. This is easy for the service provider to manage centrally because of the web-based nature of the application.

6.7. Improvements

Following the trial, several improvements have been identified:

- The system can be more accurate and increase data about equipment interaction data by including SBCs in shovels in addition to beacons.
- A data search can reveal when trucks are in the same place at the same time, giving good insights for hauling route design.
- The accuracy of the GNSS is currently 6 m (approx.). Real-time kinematic (RTK) correction is being considered to improve the location accuracy.
- An inertial measurement unit (IMU) can be added to measure displacement and location, supplementing GNSS coordinates, and can also provide additional information related to vibration that can give a richer data set for process improvement.
- Optimisation algorithms can be applied. For example, a model that provides the shortest route, or that alerts the truck operator when a shovel is available for loading, can easily be implemented on the server, which can communicate with drivers through mobile phone services.

6.8. Limitations

- The system discussed in this paper is dependent on the presence of mobile phone signal. If the information cannot be transmitted immediately through the mobile network, it can be stored locally in the SBC and transferred periodically, but it will not work in areas with no mobile data coverage. Considering the importance of an FIS in reducing mining cost as well as the medium-scale mines' budget constraints, low-cost communications technologies such as LoRa [56] could be used to reduce the lack of communication if mobile signal is unavailable. This kind of technology enables a robust FIS, keeping the system cost down.
- Dilution of precision in GNSS systems results in inaccuracies in the system if the pit geometry is deep and narrow, blocking the satellite systems. The instruments can fail in deeper pits or mountainous areas because the GNSS signal can be shadowed. The lack of GNSS coverage can be overcome through more widespread use of Bluetooth beacons in key positions for locating equipment.
- The system relies on the 12 V supply in the cab, so its reliability can be manipulated by truck operators. There is real potential for operator interference with the system that has not been investigated in this pilot project. If necessary, the system can be connected directly to the battery and placed outside the cabin, but the system will require redesign for harsh environmental conditions.

7. Conclusion

The Fleet Information System and the case study carried out at Altos de Punitaqui Mining Company in Fusionada Open Pit mine, lead to the conclusion that a low-cost IoT including Connected Devices, a Cloud Storage System and an Application System can replicate some of the functions of commercial FMSs such as calculations of the number of truck cycles per shift, the shovel loading time, truck and shovel positioning, tonnes moved per day, truck speed, average fleet efficiency and developing mining benches to monitor and optimise mining production.

The system tracks essential production data, enabling improved management and seriously improving the chances of the mine to continuing to operate, providing jobs during inevitable times of low resource prices.

The system can be installed with no IT skill personnel and the information can be analysed on any device connected to the internet using a friendly web-based dashboard that offers real time information or reports such as heat maps for routes that have truck congestion or trucks that exceed speed limits.

The current manual management of truck allocation and time measurement on medium-size mines can be replaced with a low-cost IoT that will rapidly return its cost in productivity increase for the mine.

Low-cost IoT SBCs and Bluetooth beacons, connected to users through cloud storage and an application system open a real chance for medium-scale mines to access the benefits usually associated with unaffordable FMS technology. Although the system that was piloted does not add automatic route optimisation, it does provide the basic data necessary to do so and will be upgraded toward that ultimate objective.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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