Instrumentation and Data Collection Methodology to Enhance Productivity in Construction Sites Using Embedded Systems and IoT Technologies

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Abstract

Construction projects are dynamic environments which are hard to monitor in real time conditions. Thus, traditional practices for productivity estimation, such as historical data analysis, do not provide enough information for decision making. This project proposes a new methodology to instrument and collect data in construction sites using embedded systems and IoT technologies. This solution is efficient in terms of energy, range, costs, and security of the data. In particular, it deals with one of the main challenges of implementing a Real Time Location System (RTLS). That is, we use an indoor technology and adapt it to the unfavorable conditions of constructions sites. The designed network is implemented in three different type of construction projects. Results show that our methodology can be used to determine the level of productivity of personnel in site and to record, analyze and rank their performance in different types of construction activities. This allows decision makers to promptly present alternatives to improve productivity, thus, achieving a positive impact in the fulfillment of the scope, schedule, budget, and quality of the projects.

Keywords

Instrumentation • Data collection • Embedded systems • IoT • Productivity • Construction sites

76.1 Introduction

Construction projects are complex and dynamic environments which are hard to monitor in real time conditions. Thus, preserving safety and accomplishing acceptable levels of productivity has become a main priority and challenge for Engineering and Construction [1]. In addition, traditional practices for productivity estimation, i.e, historical data analysis,

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do not provide enough information for decision making. Therefore, using new technologies to monitor variables in real time (personnel productivity and equipment usage) is essential to improve the design, analysis, planning and control processes in construction fields, as well to create programs to guarantee the workers' welfare at the workplace. Projects with automatization and information technologies (IT) integrated to their processes, could increase their productivity levels between a 31 and a 41% [2]. Moreover, using IT in working zones to enhance workers productivity, could also help to reduce the shortage of skilled workers in the construction industry [3]. According to studies conducted by McKinsey & Company for the Colombian Chamber of Construction [4], Engineering and Construction productivity levels in Colombia are behind global indicators. This is mainly because the adoption rate of new technologies is about 14%, in contrast to the international indicator that is around 48%. Other industries have tried to incorporate Internet of Things (IoT) technologies as a solution for real time measurement, analysis, and data management, which have been adapted to the construction industry, i.e the use of QR codes to identify workers and register their entry time to a productive zone. However, this is not an automated system because it requires human intervention, so the accuracy of the measurements is not guaranteed [5]. Other systems collect data automatically by using different kinds of wearable devices using Bluetooth o UHF Bluetooth and RFID technologies. Furthermore, there is a particular interest in tracking assets using Global Positioning Systems (GPS), Real-Time Location Systems (RTLS), and other geo-positioning technologies [6] and some laboratory prototypes have been presented combining Bluetooth technologies and WiFi networks for indoor location and real time tracking. Nonetheless, these laboratory tests were done within a controlled environment and conditions such as weather, network availability, and security were not taken into account [7]. Regarding the networks used for this kind of applications, the Low-Power Wide-Area Network (LPWAN) has transformed the way connections are made under the 4th Industrial Revolution because in contrast to the other similar solutions available in the market, they are low-cost, consume low energy and are wide range networks [8]. In [9], a review of different works related to RTLS in construction projects such as GPS, RFID, UWB, WLAN, Ultrasound, Infrared (IR), and Computer Vision System is presented. Additionally, there are other techniques that use the proximity of a Bluetooth Low Energy (BLE) device to different nodes with known positions in order to obtain the location of the device by triangulation methods [10]. This technology is known to be extremely accurate indoors and low cost, but it only provides positioning data in two dimensions. Other solutions have been identified worldwide for productivity measurement and analysis through embedded systems, using different types of sensors or hardware [3, 11–13]. However there is no evidence of their application in construction projects. For this reason, more efforts are needed regarding the control and planning of activities in construction sites [14].

This work presents a new methodology for data collection and analysis in dynamic environments using embedded systems and IoT technologies, including indicators to determine productivity levels of workers and equipment. It deals with one of the main challenges of implementing a RTLS in environments other than indoor locations. That is, we use an indoor technology and adapt it to the unfavorable conditions of constructions sites.

76.2 Methodology

We designed a wireless sensor network using Long Range (LoRa) technology for the communication between devices. This proposed system was designed to evaluate the productivity of people in work zones and includes BLE devices, sensor nodes to receive and transmit data, a brain or central node to integrate information between the sensors and the cloud and a platform in which information can be displayed, as described below and depicted in Fig. 76.1.

- Personnel and minor equipment devices: These are BLE devices installed on workers helmet and minor equipment, identified with a 32 digit hexadecimal number named universally unique identifier (UUID). The devices transmit a signal that can be used to determine the distance through the Received Signal Strength Indicator (RSSI), which is the measurement of the power present in the received signal at the sensor node.
- Sensor node: they scan the UUID and RSSI from personnel and minor equipment BLE devices detecting their presence in the working area. These sensor nodes communicate with the central node via LoRa.
- Central node: they work as a gateway that sends the information to an IoT Hub via WiFi or Ethernet. To ensure that the data collected can be transmitted to the cloud, the central node is located in the project offices and connected to a reliable WiFi network.
- Cloud service platform: After data is processed, the platform displays information such as the time that workers spend in specific areas of the project, the time spent on specific activities by zone and occupation, among others.

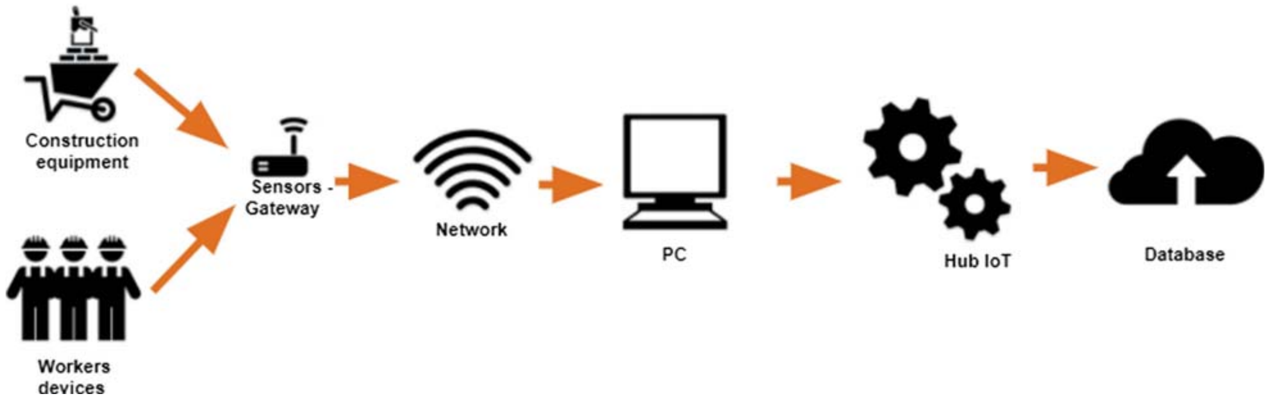

Fig. 76.1 Network design

Table 76.1 Projects specifications

Project	Dimensions	Construction system	Number of workers
Commercial building	8 floors, 4 basement plants 2 towers	Conventional column—beam—slab frame system	246
Residential building	26 floors, 672 apartments 4 towers	Conventional column—beam frame system	480
3D printed house	25 m^2	Additive manufacturing	7

Field measurements are made automatically, monitoring productive times of workers and usage levels of minor equipment. The designed network was implemented in three different types of construction projects: a commercial building, a residential building and a 3D printed concrete house. These projects are located in Colombia, South America, where normally the reliability of wireless connectivity and stable energy availability is not fully guaranteed. Table 76.1 presents some characteristics of the projects.

The system was implemented within the framework of a productivity methodology that's been recently used in all the projects of the company which enhances the measurement of labor hours in construction sites. For this reason, our complete designed system is being used as a tool for the aforementioned methodology as an input to generate performance indicators.

76.2.1 System Evaluation Procedures

Prior to the installation on field, laboratory tests were carried out to validate the operational and communication performance between all network elements in a controlled environment.

Stability laboratory test: Laboratory tests were conducted in order to verify the signal stability of the acquired devices and to validate data acquisition. For this purpose, 4 BLE devices were placed at a known distance, in line of sight, and RSSI values were read every 5 s. The standard deviation was expected to be less than 2.8 dBm for all cases.

Signal noise evaluation on laboratory: Also, normality tests were performed in the laboratory to characterize the noise present in the RSSI signal of the BLE devices. In addition to the laboratory tests conducted to validate communication between nodes and devices, field tests were carried out to evaluate the performance of the equipment and the entire system under construction conditions.

Reliability evaluation on field: A reliability test was performed to verify that nodes in production areas were constantly receiving information from installed devices. For this purpose, two fixed BLE reference devices were left on each of the nodes installed on site. Thus, a signal was expected to be received constantly and with the same strength. The data sent by the devices and received by the collector, was sent to the central node which then uploaded it to an assigned database. The data of each reference device was analyzed to evaluate the deviation between the power strength and frequency of the signal on each of them.

Sensors precision evaluation on field: This test consists in placing two nodes (A and B) at the same place within the construction site to identify whether the information received by node A is the same as the received by node B. In order to verify that both identify the same number of devices, a portion of the database was evaluated. The number of devices detected by each one of these nodes in a given period of time was compared.

Devices precision evaluation on field: Three BLE devices are positioned at the same place on the construction site for a time interval of more than 30 min at three known distances within the range of coverage of one of the nodes. The collector node located at a known distance from these devices receives the data and sends it to the central node, so that the RSSI values for each of the devices and the difference between each of them can later be verified in the database.

Distance and signal power evaluation on field: These tests allowed us to evaluate the level of congruence between the distance calculated through the received signal and the real distance. The information obtained from precision device testing is used to determine the signal strength at a given distance.

76.3 Results and Discussion

In general, results show that our methodology can be used to determine the level of productivity of personnel in site and to record, analyze and rank their performance in different types of construction activities. Tests results in laboratory are described first and then results for the system performance on field and analysis of the data are presented.

76.3.1 Test Results

Panel A in Fig. 76.2 shows an example of the reliability tests performed in laboratory, where the RRSI values obtained for a group of four BLE devices at two different distances are observed. Upper lines belong to devices placed at 30 cm of the node, the lower lines depict devices at 6 m. The standard deviation for devices at 30 cm was 2.2 and 1.7 dBm for devices at 6 m. Therefore, the precision is improved with the distance. Considering the dimension of construction projects, this test is useful to validate the accuracy of the data that can be obtained with the designed system.

Panel B in Fig. 76.2 shows a histogram for one of the devices at the two different control distances used in the test. The *x* axis represents the magnitude of RSSI and *y* axis the frequencies. The data accumulation shows the reliability of the signal for each distance.

Results for field tests carried out at the different types of projects show that there are similarities in the way how the elements of the network should be managed but the installation conditions are independent of each type of project. For example, in a commercial project with larger open spaces and fewer divisions, less nodes are required than in a residential project, which has more divisions or walls that could interfere with the signal, thus affecting the measurements. In a first phase of the project, a SigFox network was installed with good communication results during the construction of the

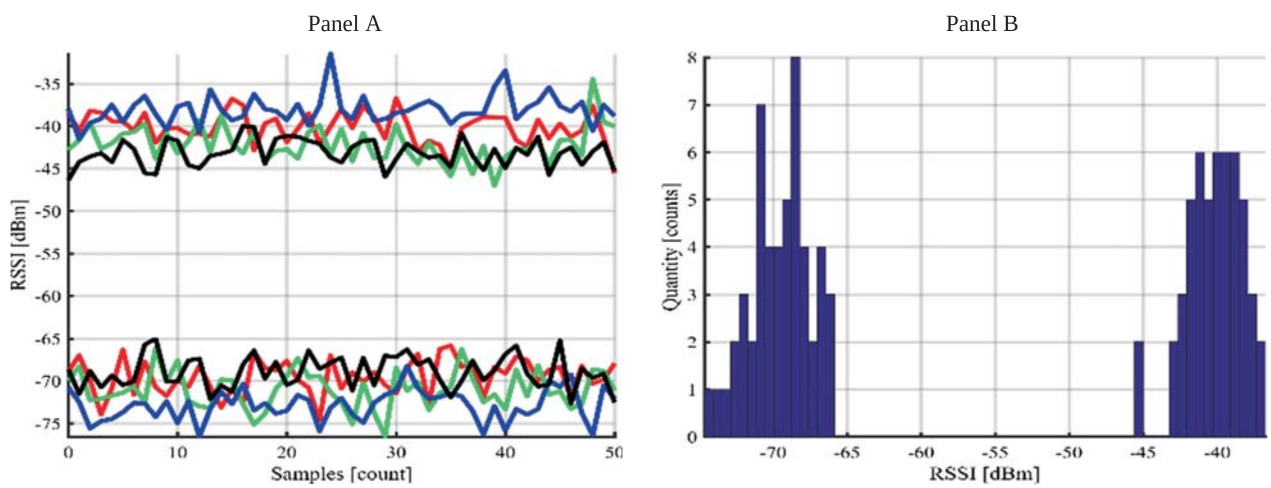

Fig. 76.2 BLE devices RSSI and FDP

foundations of the project. However, once the building started to grow vertically, communication problems arose due to the interference generated by the structure. For this reason, the network was replaced by a LoRa network, improving performance and achieving a coverage range up to 10 m underground. System field test results were kept within the tolerance levels described in the methodology.

76.3.2 System Performance

We designed a solution which is efficient in terms of energy, range, costs and security of the data. On the one hand, to ensure the interoperability of the system, personnel devices were set to transmit data at 1 Hz frequency and the nodes were allowed to receive multiple data at the same time. Arrays of twenty data were sent to the coordinator, which also sent a message to the sensor, verifying the reception of information.

From a technical perspective, the developed system performed well. LoRa networks were used for this application to support long-range communications between objects connected to the network. In general, other existing solutions (i.e RFID, GPS, UWB, WLAN, among others) require higher implementation costs when compared to our system, because they combine different technologies to reduce the influence of the construction environment to the accuracy of the evaluated systems. In terms of the internet upstream speed required to upload data to the IoT Hub, the system can reach maximum levels of approximately 1.2 MB during a day. This is low, considering connectivity conditions in construction projects in Colombia.

Devices installed on workers have a battery life of approximately 1 year, this means that they don't need to be charged. This enables the device to be changed only when the helmet needs to be replaced due to Health and Safety regulations. Each device is associated with a worker ID, their name, his contractor name, and the activity they perform on the job site. This way, it is possible to know personnel working trends. Worker's devices are the same as the ones installed on the minor equipment, so their management and operation is similar.

Designed sensors are transportable, that is, they can be relocated according to the construction program. Their configuration is adaptable so they can be connected to any project network and also they can be taken and installed in other projects. Thus, the system can be adapted to any particular design, size and progress of each project. Also, the designed nodes are composed of simple elements. They are located in hard access places, improving the security of the system.

Many project monitoring systems, whether manual or (semi-) automated, cannot be implemented due to economic constraints [3]. It is essential to emphasize that the designed network uses low cost components, reducing the costs mainly in the sensors manufacturing, increasing the chance of installing more of them on the construction sites and therefore improving the coverage in productive zones.

76.3.3 System Adoption and Implementation

The implementation of the system was made initially with construction engineers and workers that were aligned with productivity strategies in the company. This was useful in order to break adoption barriers principally with construction workers that could be resistive to this kind of measurements. At the beginning, this was a major challenge considering cultural barriers in construction workers. For this reason, workers were instructed on the importance of this project, the sensors functioning and the care that all devices needed so the system could be used to increase their welfare, as it can be linked to safety programs. This improved their acceptance towards the implementation of the sensors. The training sessions were led by the construction foreman who helped us transfer this information to the crew and during the implementation. In terms of the customer experience on field, workers manifested that the device is small, lightweight and it doesn't interfere with their activities.

Regarding the platform, it could be used by Project Managers, Construction Engineers and Productivity Department personnel.

76.3.4 Productivity Measurements Analysis

Figure 76.3 shows the probability of finding a worker in a productive zone in a day. In this figure each panel represents a different type of project. Panel A shows results for the residential building, panel B for the commercial building and panel C for the 3D printed concrete house. Regarding the functioning of the entire system for productivity purposes, results show that for a working session from 7 am to 5 pm, there is a reduction in the work activity for residential buildings at 9 am and at 12 m, which coincides with the break hours for breakfast and lunch, respectively. This is more evident in panel A in Fig. 76.3. Our results show that these granted break periods are extended for more than the established hours. This result was linked to the layout of the construction site, implying that decisions could be made so work areas are better distributed, thus guaranteeing conditions of productivity while simultaneously improving the safety and well-being of the employees.

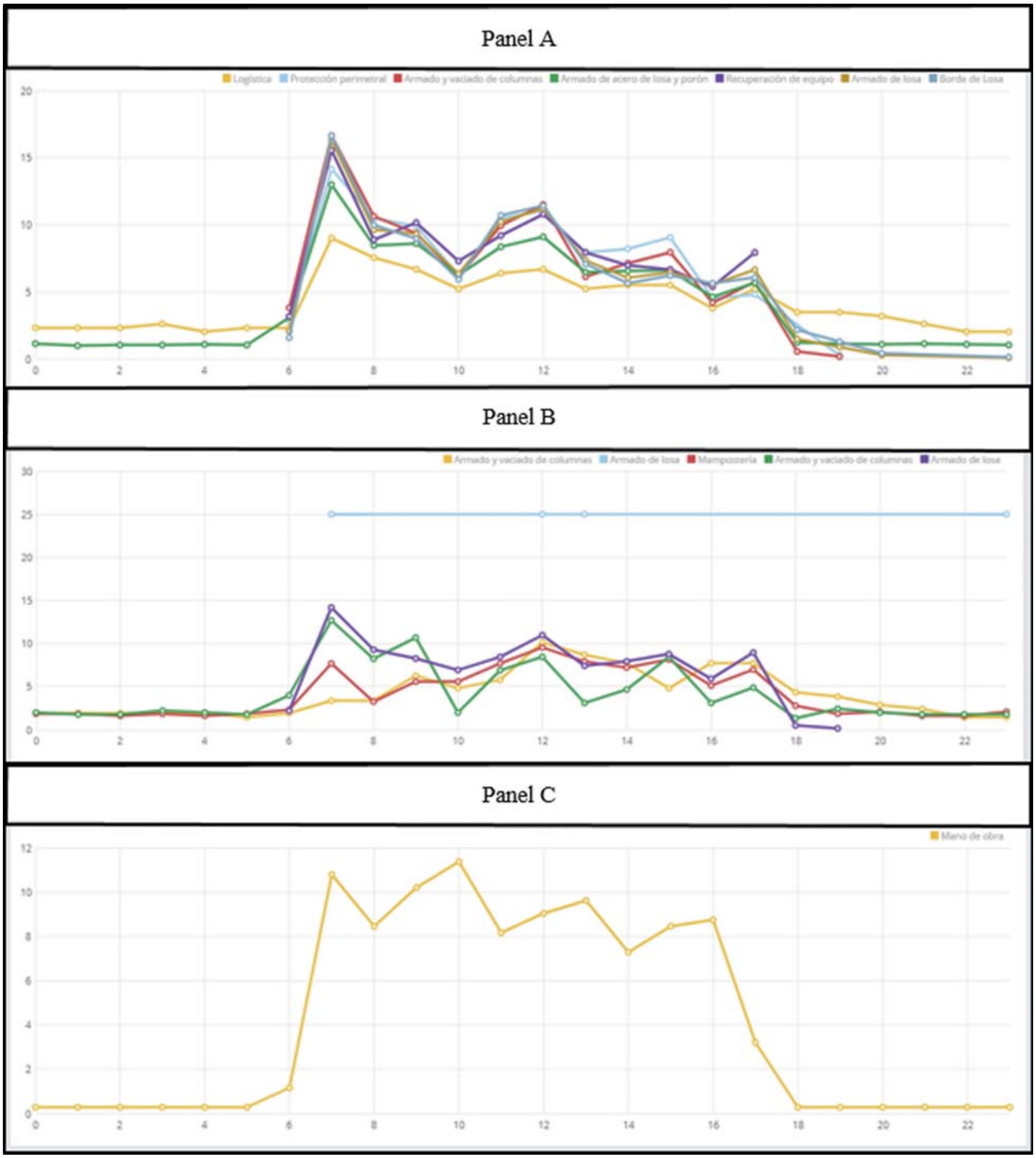

Fig. 76.3 Timeline with activities development in productive areas for residential buildings

Regardless of the differences between construction projects (Table 76.1), there are similarities mainly in the productivity hours during the day. High levels of work activity were evidenced in the early morning hours, while in the afternoon lower rates of work can be observed and a similar distribution of the personnel for the different activities that are executed in the same period of time and zones. This is even more significant for the residential project (Panel A in Fig. 76.3) in which each floor is similar to the other. This encourages a work method divided by productive units with more standardized processes, reducing nonproductive time.

Our results show that 75% of working hours during the construction of the main structure of the building correspond to the slab construction, while 18.3% is used for column construction. Although most of the activities meet the regular working schedule, there are some that are frequently extended beyond planned hours. That is the case of steel slab assembly, column casting and the activities carried out by the logistics teams, including the reception of material on site.

The monitoring of the hours spent by workers in productive and non-productive areas of the project shows that the project's operative personnel spend an average of 16% of their time in non-productive areas, including spaces such as the construction site warehouse, dining rooms, dressing rooms and bathrooms.

One of the main impacts of this project is that we were able to show that it is possible to generate information that helps to implement and evaluate productivity strategies in construction sites. Enhancements in the process of programming the work activities are presented, by supporting the corporate productivity methodologies in the projects with the information provided by the system. Additionally, less man working hours are required for productivity evaluation, due to the automation in the measurement and collection process of this information, increasing the scalability of this process.

76.4 Conclusions

Based on the implemented solution, it is possible to identify the percentage of time spent on each project for each one of the activities within the construction site, validating the certainty of the results with the work schedule. Likewise, the simultaneous monitoring of productive and non-productive zones allows us to identify periods of time that do not add value to the operation, such as waiting times at the warehouse of the worksite.

The versatility of the devices and the designed network was evaluated. The implementation of the system was successful in the different types of projects, proving that it is possible to introduce an instrumentation and data collection methodology with embedded systems for productivity analysis in construction sites, considering all the implementation variables from the technical, social and economic perspectives. This condition supports the system's necessity to be scaled up in a greater number of construction projects in order to obtain enough information to generate strategies for the improvement of the operation.

From the technical perspective, the LoRa network used in the project, is satisfactorily adapted to the construction site's distance and interference requirements, being the most appropriate option in terms of cost and performance for this application. Consequently, the future embedded systems developments applied to our construction projects, could be added to these networks in order to guarantee an accurate transmission of the data collected.

One of the future technological developments proposed for our system is an improvement of nodes, so they can be able act simultaneously as routers. This will allow the network to be implemented in larger projects. Likewise, the viability of implementing an alarm system to detect when devices are disconnected from a power source will be evaluated. Also, integrating the developed system with Building Information Modelling (BIM) methodologies is of interest, since levels of productivity in working areas and the localization of the employees could be carried out within a three-dimensional model of the project.

The obtained results allow us to plan to scale up this methodology to more building projects. In addition, this development will be connected to the personnel access control systems at the entrance of the projects, achieving a complete measurement of man working hours that can be transferred to the company's ERP systems, optimizing project planning processes.

Finally, it is important to point out that with this kind of applications it is crucial to give value to the collected information, turning IoT implementations into income generators that allow the exchange of valuable information to accelerate business innovation processes, as described by [15]. From this perspective, data collected by the devices is an important source of information that can be used with data science methodologies to detect trends in real time. This will allow decision makers to promptly present alternatives to improve productivity, thus, achieving a positive impact in the fulfillment of the schedule, scope, budget and quality of the projects.

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