Real-time Positioning via LoRa for Construction Site Logistics

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Abstract –

Tracking and monitoring resources in construction is of great interest to an industry that is in the continuous pursuit of reducing waste. Real-time location sensing technology like Global Navigation Satellite Systems (GNSS) and/or in combination with Radio Frequency Identification (RFID) have already been introduced in commercial applications to report the position of valuable construction resources such as equipment or materials. While several other communication protocols exist, unfortunately little is known about the performance and applications of LoRa (Long Range), a wireless data communication technology for very-long-range transmissions up to several kilometers at low power consumption. This paper first introduces the need for such technology and then explains the integration of LoRa in an Internet of Things (IoT) network, which enables to connect, collect, and exchange data for construction applications. The novel focus of this study is the evaluation and testing of LoRa in realistic construction work environments. The experiences made with the developed LoRa-technology are in particular useful for demonstrating the applicability of LoRa in the construction logistics and lean management sectors.

Keywords –

Building Information Model (BIM), construction resources, Global Navigation Satellite System (GNSS), Internet of Things (IoT), logistics, Long Range (LoRa), Radio Frequency Identification (RFID), tracking and monitoring, Ultra Wideband (UWB).

1 Introduction

Today’s construction sites in Europe have become more international due to laws in the European Union (EU) that call for competitive tenders for most of the public works. A bundle of evaluation requirements exist; some examples are: (a) company experience (i.e., previous work, years in business, geographic territory, previous customers), (b) organizational structure (i.e., management processes, operational procedures, hiring and training programs, turnover), (c) quality performance, (d) safety records, (e) senior management experience, (f) current projects, and (g) financial strength. These and more influence the selection of a qualified contractor. While owners, financing lenders, and insurance agencies demand lowest possible risk in any of the aforementioned criteria, little focus has been set on measuring a contractor’s ability to track and monitor its operation aside from running its business.

Another motivation for conducting this study originates from research on lean construction. Results on monitoring shell and interior construction show that waste times of 19 % are directly avoidable [1]. Some of the most wasteful activities observed in this study are reported as unnecessary ways and handling of material (10%), searching for equipment (6 %), and waiting for equipment (3 %). The same study sees further potential for the optimization of construction operations: an additional 16% of the total working time could be saved by reducing manual transport (9 %), information gathering and delivery (4 %), and clearing and rearrangement (3 %). Multiple other research studies, some of them using advanced technologies, found similar potential savings once construction site operations follow lean principles, i.e., optimizing the usage and disposition of construction machines, reducing material search times and idle times of equipment [2].

Fortunately, in recent years leading contracting organizations have been starting the adoption of technology that assists in some of the time-consuming and vulnerable tasks of performing the daily management of operations at their construction sites. One of such tasks, as highlighted originally in research by [3-5], is tracking and monitoring construction materials and equipment. Grau et al. [5], for example, called for a reduction in wasted work time for unnecessary ways and waiting and non-optimal disposition of equipment or materials. Their study demonstrated an 8:1 return on the investment and an overall 4.2% productivity gain once intelligent material tracking is applied.

While monetary benefits such as the expected gains from productivity improvements are often the main driver for a change in the existing construction business processes and operational practices, availability and retention of qualified workforce is yet another major issue that has to receive more attention in many contracting organizations [6]. Construction workforce at all levels has typically different backgrounds, e.g., education, experience, skills, and language. Measuring the impact of applying novel technology into practice and how well it potentially benefits or is eventually disliked by the workforce has yet to be explored in greater detail.

For the above mentioned reasons, namely leveraging technology for construction site operations monitoring and adoption by its workforce, this study investigates a novel communication protocol called LoRa (Long Range). The following sections of this paper are structured as follows: first a brief introducing on the shortcomings of existing tracking and monitoring technologies in construction is presented. The sections thereafter explain the developed LoRa-approach by measuring the location error, checking the reliability, testing the usability, and evaluating the practical benefits for implementation in construction operations. A discussion on the remaining limitations and an outlook for future work conclude this paper.

2 Background

While a vast body in the construction-related literature exists on location tracking and status monitoring, the scope of this review focuses on the use cases for the Internet of Things (IoT) and technologies as they relate to construction material and equipment location tracking and monitoring.

2.1 Internet of Things (IoT) in construction

The Internet of Things (IoT) stands for the digital mapping of the physical world and the ability to monitor and manage real things in the digital sphere [7]. With the IoT, data gathering by sensors and processing digitally via the cloud, for example, can be performed in a much faster and less complex way than real world objects and processes. This enables acceleration and optimization by data-driven decisions of many construction systems and businesses.

Already available in the IoT is the digital information from build-in sensors, computers and personal devices like smartphones. In a next step additional distributed sensors, for example installed on construction materials and equipment, complement this set of data. The data transfer of such assets is typically wireless without requiring human-to-human or human-to-computer interaction. The data is also collected on clouds for easy access and for further evaluation.

Decision criteria for wireless distributed sensors are typically the cost of hardware and use, usability, reliability, robustness, and lifetime. For any successful innovation in construction, these factors have to be fitted to specific needs in an organization's use cases.

Since the operation of many construction sites is still very complex and dynamic, much of it would benefit from wireless distributed sensor applications, in particular as they relate to location tracking and monitoring. Often named use cases (bold boxes) and some of their positive influences (grey boxes) thereof for location sensing are shown in an overview in Figure 1.

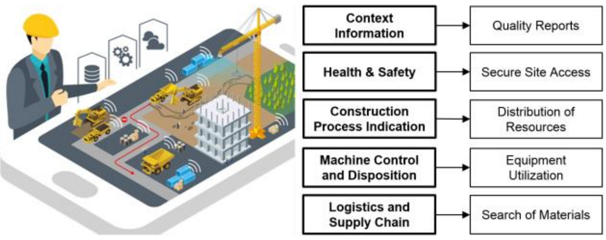

Figure 1: Typical construction uses cases and outcomes of distributed sensing [courtesy of Robert Bosch GmbH]

2.2 Location tracking and monitoring

Several ways exist to measure, communicate, and use positioning data. We define the term *location tracking* for the continuous gathering and transmission of a resource's (material or equipment) positioning data over time, while we speak of monitoring in terms of the simultaneous processing of the data to yield information which is then used in specific construction applications, such as resource location or resource status monitoring.

There are several dedicated systems for determining geolocation and time information. One of the most popular ones are grouped under the umbrella of *Global Navigation Satellite Systems (GNSS)*: GPS, GLONASS, Galileo, or BeiDou. These consist of satellites that continuously transmit data about their current position and time. On earth, a receiver monitors multiple satellites (a minimum of 4 of any GNSS) and logs the precise position in a high resolution time interval [8]. Clock calibration data and correction data is stored in the almanac (an internal database).

While the use of GNSS in *professional surveying applications* such as performed in earthwork activities (i.e. automated machine guidance) requires very high precision, many outdoor construction applications focus on *location awareness applications* that demand lower precision (typically within the meter range) [4-5, 9-11]. In both scenarios, the largest errors in GNSS positioning are attributable to the atmosphere such as distortions caused by the ionosphere (i.e. signal delays caused in space), troposphere like bad weather (i.e., cloud coverage), or multipath in dense work environments (i.e., reflections or obstructions from nearby high-rises).

Correcting such errors is expensive and often requires additional technologies. For example, telematics solutions for construction equipment are typically based on GNSS receivers for localization sensing. They use cellular networks for sending the data to a database where it is further processed. Although a GNSS receiver with current data in its almanac can acquire satellite signals more quickly (which helps determining the position faster), several minutes are generally needed to initialize the signal reception. This requires the receiver to be turned on (thus consuming power) and works only outdoors with a clear view (i.e., line-of-sight) of the sky. Alternative methods to get a faster GNSS-fix exist. A-GPS, for example, get their almanacs and approximate position from network stations (BTS, NodeB, eNodeB) based on GSM or LTE technology. It is therefore generally cost-prohibitive for tracking applications that would require to equip large numbers of items. Although their form factors (i.e., dimensions) have decreased in size over time, these reasons ask for alternative technologies.

A second technology closely related to this study and already applied in construction operations is called *Radio Frequency Identification (RFID)*. RFID solutions allow tracking, but require a tag located on the desired object. There are active, semi-active/passive and passive RFID tags consisting of scanners or antennas that read them [4-5, 12-13]. Depending on the type of RFID, the read range of the antenna can be from centimeters (passive tags) to several dozen or hundreds of meters (active tags) [14]. The advantage of passive RFID technology is that no internal power source is needed on the tags. These tags can be small in size, inexpensive once fabricated in large numbers, and attached to almost every type of material (even metal) [15].

Since RFID often transmits just the tag's identification number over shorter distances, no additional data like its precise positioning coordinates are available. A user demanding the terrestrial geolocation of construction assets in a large laydown yard, for example, thus has to combine RFID tags and antennas with a mobile GNSS receiver on a ground-based vehicle [5] or an unmanned aerial vehicle (UAV) [16]. Further software technology for data processing and visualization or managing of the timestamped geolocation information is also needed. As explained, the costs for implementation, use, and maintenance add up quickly (i.e., requiring also a licensed person for safely operating a UAV).

Other communication protocols based on radio frequency, including Near Field Communication (NFC) and Bluetooth Low Energy (BLE) for mobile applications, offer – as outlined in research – shortcomings. Imprecise and short read range limit their application in location tracking [17]. To name a few additional communication protocols that have been applied to or tested in construction are Zig-Bee, Z-Wave, Wi-fi, and Ultrawideband [18-19]. Although they were applied in specific scenarios perhaps relevant to construction, for example wireless personal area networks (WPANs) for high data transfer rates in home automation and communication, some of their distinct limitations are: high power consumption, additional signal sensing infrastructure requirements (e.g., number of nodes), low security standards, and limited range.

An alternative approach for location tracking are mobile radio standards. The Global System for Mobile Communications (GSM), for example, was first deployed in Finland in 1991 for fully digitalized mobile networks [20]. More recent distributed sensor-IoT solutions in smart city applications use unlicensed ISM bands (Industrial, Scientific, and Medical Radio Bands). They work in ranges of some kilometers and with very low bandwidths, so called Low Power Wide Area Networks (LPWAN). Most common LPWAN networks are Sigfox and LoRa. Both are a special design of autarkic distributed sensors with very low power consumption and cost of use. The main difference to LoRa is that SigFox is a network provider and any sensor devices to be used with SigFox has to be integrated within the SigFox network. LoRa is an alliance with more bandwidth than Sigfox and allows to build or use an existing LoRa network.

2.3 Introduction to Long Range (LoRa)

LoRa is filling a gap in wireless communications (Figure 2). Public LoRa-networks are currently being deployed all around the globe [21]. Just like mobile phones in a mobile phone network, LPWAN devices will be able to operate in public LoRa networks [22]. Private gateways will supplement public networks in the transition period.

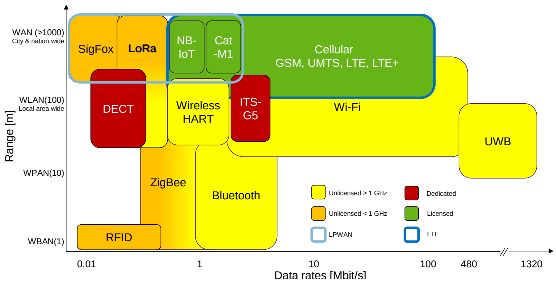

Figure 2: LoRa filling a gap for wireless communications

LoRa is specialized for the requirements of the IoT. LoRa offers secure bi-directional communication, localization, and mobility of services without the needs of static and complex installations. The open non-profit association called the LoRa Alliance has set itself the objective to standardize LPWAN to enable the IoT to guarantee interoperability in one open global standard. LoRa typically has a star-of-stars-topology. As shown in Figure 3, the end-devices (LoRaWAN slaves) communicate via LoRaWAN with the gateways that are within reach. A gateway serves as a transparent bridge by using a network connection (e.g., realized via GSM) to send the received data to a network server or vice-versa.

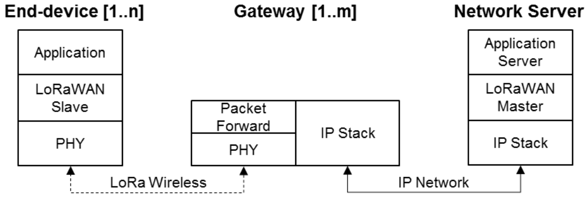

Figure 3: Communication in a LoRaWAN network (modified, after [21])

The communication between the gateway and end-device depends on data rates and frequency channels [23]. LoRaWAN data rates reach somewhere from 0.3 kbit/s to up to 50 kbits/s. However, because of the regulated restrictions on the 868 MHz frequency, only a maximum broadcasting time of 2% of the run time is permitted. At first look this restriction might limit many useful applications for LoRa in construction. However, the maximum throughput and probability of successful transmissions enable the tracking of thousands of objects.

Another increasingly important topic is security. LoRaWAN offers a multi-layer encryption for protecting sensitive data [24]. Regulations are Network Level Security and Unique Network Key (EUI64). A Unique Application Key (EUI64) provides security at the application level, and Device-specific button (EUI128). The encryption is particularly helpful once public wide area networks replace the local gateways on a construction site. Depending on a use case, sensors equipped with a LoRa end-device can transmit messages and receive acknowledgements or responses by listening to the network. This happens after sending requests on fixed intervals or in an always-on mode. The more power consuming is the always-on mode. The always-on mode, however, reduces the latency for time critical purposes, such as applications in infrastructure health monitoring. Optimized power consumption results in a battery life of many years. Theoretically, this enables LoRa sensors and devices to send and receive information even when located indoor or underground [23].

3 LoRa architecture

Many practical applications exist for LoRa in construction. Examples of much needed use cases in construction that can be solved are: locating and dispositioning assets, tracing off-site construction and checking-in inbound deliveries, finding of implements and tools, organizing fleets and cooperatives, monitoring machinery, geo-fence alerting, managing inventory and optimizing workflows, shock or temperature monitoring, maintenance or theft alerting, counting operation hours, and billing and providing evidence of back-office services. These examples in mind led to the design of a suitable LoRa-IoT architecture. The result is shown in Figure 4. While only providing low data rates, the main advantage of using GSM/LTE is the outdoor distance coverage. It makes it attractive for use in the proposed wide area field test. For sending the sensor data incl. the received position data from a built-in GNSS receiver the 300 ms latency of the LoRa is more than sufficient. The technology, incl. the LoRa device called thereafter TRACI, was later tested in realistic working environments common for construction.

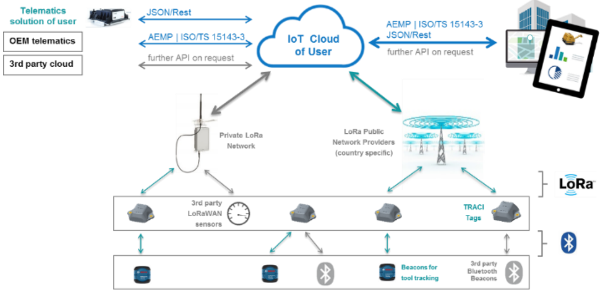

Figure 4: The LoRa architecture [image courtesy of Robert Bosch GmbH]

A TRACI tag with its integrated sensor stack delivers the following data, among other data:

- Network: LoRa - EU868 - Europe 863-870MHz
- Radios: Bluetooth 4.2 / passive NFC
- 3-axis accelerometer (+/- 2g 1mg; +/- 4g 2mg; +/- 8g 4mg; +/- 16g 8mg; fmax 2kHz),
- 3-axis magnetic field (3-axis, (+/- 1300µT 0.3µT),
- GNSS (ublox module) sensors
- Size and weight: 0,11 x 0,082 x 0,038m; 0.17 kg

4 Case study application and results

4.1 Geolocating

The position of the TRACI tag it determined through use of an embedded GNSS module. It has been found from interviews with leading construction organizations, that many use cases in construction require a position accuracy of less than 10 m which current Time Difference of Arrival (TDOA) methods for LoRa currently cannot deliver. Position accuracies of smaller than 200 m for LoRa TDoA can only be achieved with a high density of LoRa base stations (at least 3 gateways).

While this may serve some construction applications, like theft protection of expensive equipment, achieving lower error rates with denser networks would substantially increase the overall implementation and operational cost [22]. This is why TRACI needs a build-in and low-cost GNSS module and its performance must be tested.

The GNSS hardware (as explained before) used in this study achieved a *Center Error Probable 50%* (CEP50) of 2.3 meters (Figure 5). This result is based on a 24 hour measurement duration with 86,400 values. In the measurements performed for Figure 6 the use of GLONASS and Galileo, as additional satellite systems to GPS, did not lead to a measurable improvement in the position accuracy of the TRACI tag. Additional observations from tests with the developed LoRa device in a laboratory environment included:

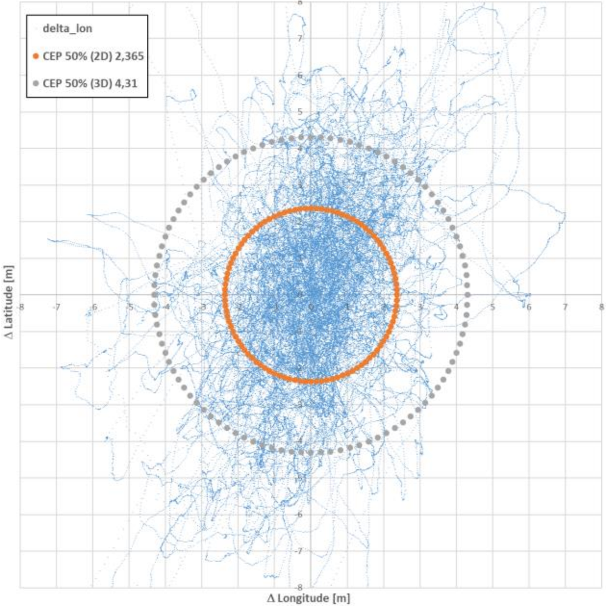

Figure 5: CEP50 for TRACI device (GPS only)

- Higher position accuracy comes at cost of battery life time. Figure 6 shows that a CEP50 increase from 2 to 3 meters can - in some cases - reduce the GPS-fix time from 100 seconds to below 20 seconds. Taking into consideration that TRACI's GPS-module consumes around 50 mA when active, reducing the CEP50 requirement can improve the battery life time of such sensors significantly.
- Due to the constraints of the limited bandwidth of LoRa, the sensor data is processed in the device itself with use case specific firmware. Sensor data is aggregated and processed in the application layer of the software. Doing so enables the transformation or gathering of (a) acceleration data or magnetic field data into operating hours of machines, and (b) strength of electric current or spatial orientation of the device itself. The aggregated data is then transmitted via LoRa to a cloud backend in compliance with the ISM-band duty cycle. From the cloud the data is shared via a JSON/REST API that allows stakeholders to add further value and build applications for different use cases.

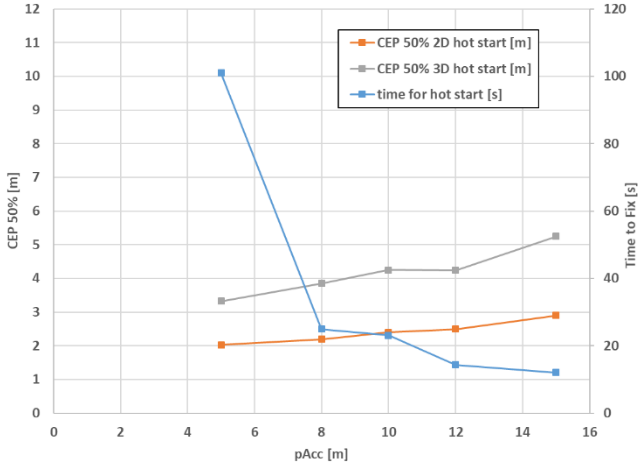

Figure 6: GPS fixe time over position accuracy (pAcc) for different CEP50

4.2 Equipment monitoring

The objective of the first field implementation of the TRACI tag was to automatically monitor a tower crane's operating time. Measurements were performed on a Wolff flat-top crane on a building construction site with a total number of 9 cranes. Usually, the TRACI tag measures operation hours based on vibration. The goal of this measurement, however, was to determine whether the acceleration signal of the motor of the main winch could derive the operation information. In case the acceleration signal is not strong enough, operation hours can also be counted with the help of its embedded 3-axis magnetic field sensor. For this reason, the feasibility of using the magnetic field signal of the motor was also assessed during the measurement (Figure 7). The gathering of the acceleration as well as the electromagnetic field data of the motor of the main winch (Figure 7, left image) resulted in data (Figure 8).

Figure 7: Implementation of Lora-tags on tower crane motors (i.e., raise/lower, move in/outwards, turn)

Figure 8: Typical machine data when accelerating the crane block: electromagnetic data shows the tower crane's activity (0 equals no crane activity)

From the large data set that was recorded, a snapshot of 190 seconds will be explored to highlight some of the findings. The motor's magnetic field signal shown in Figure 9 shows a measurement that was recorded while the crane performed several hoists (lifting and lowering) with a load of 1,700 kg at different speeds. Findings from the observation were:

- While further measurements with lighter loads did not lead to significantly different signals, loads had little influence on the magnetic field measured with the sensor.
- Acceleration measurements of the crane structure during idle time showed that the signal noise from wind and other external influences lead to vibrations on the crane with an amplitude of around 0.2 g absolute.
- The acceleration signal in Figure 8 shows, that the acceleration in most working conditions does not exceed the normal structural idle noise on the crane. Hence, the acceleration signal is not sufficient to reliably deliver the operating hours of the motor and subsequently the crane.
- The acceleration peaks at the beginning and end of the measurements are due to changes in the measurement range of the sensor and are not caused by the crane itself.
- The magnetic field components, represented by the three lines (red, green, and orange) show a strong signal which can be used for evaluation the working hours of the motor.
- The sampling rate in the data visualization tool used led to aliasing effects, which become obvious in a distorted and non-continuous signal behavior. The actual oscillation of the magnetic field does happen at a higher frequency than displayed. However, the amplitude of the signal shown in Figure 8 and the sampling rate of the sensor itself do allow for a precise determination of the actual operation hours of the motor, based on the magnetic field change only.
- Furthermore, the oscillation when working can be discriminated from the electrical holding of the load without mechanical breaks, which can be seen in Figure 8 in the first section of the measurement. Being able to differentiate between the two active modes of the motor leads to a more precise evaluation of the actual work happening.

These findings led to a more detailed investigation of the crane's activity. As shown in Figure 9, on one particular work day (24 hours), the crane was in operation a total of 7 hours and 6 minutes. For reasons of better visualization, the observation time was grouped into 40-min intervals. By analyzing the TRACI data only, the crane showed activity (bars in green color) in the intervals 22-26, 38, and 40-56. Within the intervals of activity, TRACI reported that the utilization of the crane varied (as shown by the percentage values). At all other times, TRACI reported no operation of the crane (red bars). The crane's utilization reported by TRACI was compared using the multi-moment-analysis (triple M) method [25]. The thin line (black) in Figure 9 indicates the results of a knowledgeable person briefly observing the crane at repeating, but specific time intervals. As can be seen, the manual not always overlaps with the automated data. On this particular day, this person did not record any crane activity in 6 while deviating in 4 other intervals for more than 30% from the results of the automatically recorded data. While these error show one disadvantage of the manual multi-moment-analysis method, data analysis and reporting can be delayed as well.

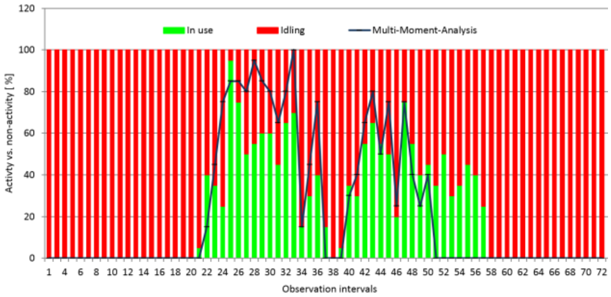

Figure 9. Crane use vs. idle time

The overall utilization of the crane given a 10 hour work shift over a 4 work day period can be assessed as the following.

- Day 1: 318 min or 53% of 600 min.
- Day 2: 287 min or 48%.
- Day 3: 314 min or 52%.
- Day 4: 284 min or 47%.

As a result, about half of the work time during the 4 days that crane was not utilized. An experienced manual note taker further assessed productive vs. wasteful activities of the time when the crane was in action on the first and last observation days. While these manually observed data points may not be compared with data from TRACI, the note taker reported productive work execution in:

- Day 1: 53.8% of 318 min.
- Day 2: 52.3% of 287 min.
- Day 3: 52.6% of 314 min.
- Day 4: 50.9% of 284 min.

This results in an overall productive utilization rate of the tower crane of about only 25%. While this data is not representative for other work days on this particular construction site, it may hint towards a larger potential for crane use optimization. This case study ended with some additional reasoning how automatically-generated crane data and its analysis might enhance its operation:

- The idle times of a crane can be recognized and subsequently optimized. Proper equipment resource allocation, such as crane availability to the competing work crews on the ground, can significantly impact a project's construction schedule, and in particular in high-rise construction where hoist times are often critical [26].
- The automatic recording and processing of crane data could be used, among other noteworthy examples, in (a) billing a subcontractor's crane use time, (b) recording the overall crane operating hours for resource leveling among all subcontractors, (c) alerting and calling for preventative maintenance tasks, and (d) overall progress monitoring of site activities based on historical estimates or real-time data.

5 Conclusions and Outlook

The construction industry is currently experiencing a change towards digitalization. Building information models (BIM), Internet of Things (IoT), mobile or smart wearable devices have become buzzwords for construction applications intended to follow lean principles. IoT for construction yet has to fully implement simultaneous data gathering, analysis and visualization. While a multitude of sensors exist to collect data, Local Range (LoRa) fills a gap in existing data communication protocols. This study has shown in an independent case study of how a novel IoT-LoRa architecture and its developed technology might be applied in construction. The study leveraged LoRa-tags in combination with magnetic field sensors on a tower crane for monitoring its activity. The results show that the technology exceeded the human capacity for the recording and the analysis of the plentiful of data that is available in construction. Future research though has to carefully evaluate the reliability of any of these technology in daily work practices (perhaps at much larger operation scale) as well as its impact on human workers. Further work may therefore focus on exploring human-technology interfaces and the richness of new information that is generated once it is applied to information models [27]. Once envisioned in applications for intelligent decision making tools, in particular as they relate to construction site logistics applications, much of the existing problems, such as uninformed decision making or unawareness of project or resource status, might be solved.

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