Smart Construction: Remote and Adaptable Management of Construction Sites through IoT

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Abstract

Construction sites for large civil engineering projects consist of very different workflows, depending on the size and type of the project (e.g., highway construction). Managing and coordinating such complex projects is a difficult task. Lack of proper digital and reliable data makes the near permanent physical presence of a project manager necessary. But even on site, they have to rely on manual and slow reporting ad hoc information gathering processes. In this article, we report our experience in using Smart Construction, an Internet of Things cloud-based platform for large civil engineering projects. The platform allows project managers to remotely manage multiple construction sites in different locations at the same time and promptly intervene to adapt their operation according to real-time data analytics results. We performed two experiments on real construction sites to collect real world data by using the platform under realistic conditions.We discuss the challenges that we encountered and the results of the performed data analysis.

Introduction

Large civil engineering projects (e.g., highway construction) tend to be very complex and challenging as the size and required budget increases. This often leads to unexpected project delays and/or increased costs. Managing and coordinating such complex projects is a difficult task. The fact that in many cases no or only sparse and incomplete data is digitally available makes frequent or even permanent physical presence of project managers necessary. But even on site, information availability is severely limited through slow reporting and manual ad hoc information gathering processes.

Construction businesses are typically still in the early phases of digital adaptation. Many processes are not tracked at all or only by using paper-based document sheets for reporting. On the other hand, the potential of digitization is enormous, as it would not just make the construction processes more efficient, but it will provide valuable tools and services through the whole life cycle of construction projects. Aspects and right strategies of this topic are discussed, for example, in the work of Mihindu *et al.* [1] and Rezgui *et al.* [2]. Until now, most of the digitization work has been done at the design and planning levels.

However, without proper feedback from the real world, these plans and models can deviate from the reality on the construction site.

To improve this situation and make large construction projects more efficient and predictable, we propose the usage of *Smart Construction*: an Internet of Things (IoT) cloud-based platform supporting the realization and management of dynamic and adaptable applications specifically suitable for construction sites.

The platform is generally usable in many project stages from early preparations to logistic tasks to the maintenance of the structure in the last phases of the project life cycle. The platform consists of smart devices deployed across the construction site, attached to vehicles and material or worn by the workers. These devices continuously stream data to storage inside the cloud platform over radio gateways distributed at the site. Furthermore, the platform's analytics component processes all incoming data and provides up-to-date information and notifications for specific events (e.g., a machine stops working, a process step is finished) to project managers or workers, thus making them able to make appropriate decisions. This is supported by the exploitation of a modeling approach allowing developers to define customizable applications [3]. These applications can be differently configured at each specific construction site and for different project phases according to the context (e.g., installed IoT devices and network), thus supporting project managers in the monitoring of the construction sites.

Related Works

The work presented in this article is related to the need and realization of an IoT cloud-based platform for the management and coordination of complex projects, namely construction sites for large civil engineering works.

In recent years, researchers started to investigate the usage of business-process-based technologies in the IoT context. Indeed, business process management system (BPMS) approaches have become an efficient solution for the coordinated management of devices [4]. Meanwhile, this novel research field has triggered the emergence of new interesting challenges [5]. This trend has led to the realization of workflow management systems (WfMS) for Industrial IoT to execute and monitor IoT-based processes, such as the one reported in [6]. At the same time, standard workflow languages (e.g., BPMN 2.0) have been extended to support sensors'/actuators' specific activities and IoT communication paradigms [7]. Different from existing solutions, our approach builds on a process-based design model that further supports the dynamic adaptation of processes, thus leading to remote and adaptable management of complex projects.

In the literature, several (open source) IoT-based platforms have been proposed. In [8] the authors present a reference architecture to plug and produce industrial IoT systems. The main purpose of the presented architecture is that of reducing industrial device commissioning times across vendor products. The Eclipse Foundation proposed an open source stack for IoT cloud platforms [9] whose aim is twofold: (i) provide an open source infrastructure enabling the realization of IoT solution, and (ii) facilitate interoperability among IoT solutions and applications. The cloud stack also provides a modular platform providing several IoT services (e.g., device registry, device management services) that is further extensible toward the creation of an ecosystem of IoT microservices. The Telus company also provides IoT-based enterprise solutions [10]. The goal of the company is to support the quick implementation and customization of IoT solutions. To this aim, it offers a novel infrastructure

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that guarantees exclusive connectivity to the realized IoT solutions by avoiding the competition with other traffic sources such as mobile devices. In particular, Telus offers flexibility, fast integration, and business continuity to its clients and their unique business needs. Although we have only mentioned some of the IoT platforms closest to our proposed solution, other platforms exist. However, `Smart Construction` differs from the existing platforms. Its focus lies in providing a practical on-site infrastructure, an application layer specific to the construction industry, and connecting both via cloud infrastructure. Existing platforms focus mainly on abstracting IoT devices and environment, providing transport protocols and data storage technologies as well as generic, configurable application interfaces and visualization solutions. In this first approach, we implemented a custom simplified version of the glue infrastructure between the Internet gateway and the application layer rather than connecting existing IoT frameworks. This decision was based on the application-centric requirements construction companies emphasized as well as their data security concerns by including third parties. Additionally, this helped reduce costs while keeping the necessary flexibility for our research environment.

Paper Structure

In the next section, we narrow down the focus to a single showcase of the platform capabilities. The following section contains a brief overview of related research. The architecture, with the major hardware and software components of the platform, is described in the next section. The platform has been implemented and used at two construction sites. Its description, validation results, and the lessons learned during these real-world tests are discussed in the following two sections. The final section concludes the work and discusses a short roadmap to ongoing and future works.

Showcase

To investigate our solution, we focus on the earthwork phase of highway construction. One of the main activities is to transport fill material from the excavation zone to the construction site, to spread and compact it, until the layers reach the required quality. Moving the excavation zone closer to the construction site is often a logical step to shorten transport times. The goal is to provide a steady supply of fill materials at the construction site, where the bulldozers spread it and the road rollers compact it. For efficiency, this task has to be performed with fine-tuned resource utilization (e.g., minimum number of vehicles on each route, closest excavation zone) and the minimal amount of necessary backup capacity.

The following problems could typically occur:

- There is not enough fill material at the construction zone, and the bulldozers and rollers are idle. Possible solutions are to increase the transfer capacity by utilizing more trucks, more routes, or closer sources.
- Trucks have to wait to be loaded (queuing) and are therefore idle. Operating more excavators or using different excavation zones could reduce waiting time.
- Excavators has longer idle times when no truck is there to be loaded. Using more trucks on the route could increase the transfer capacity.
- Unexpected delays on the transfer route. This can be caused, for example, by bad road quality. Alternate routes or using other excavation zones have to be considered.

During our requirement collection phase, construction site managers pointed out that in many available solutions the coordination happens in an ad hoc process as one or more project managers react to reports provided by the vehicle operators. This process largely relies on the individual operator observations, their reporting, and the skills of the project managers. Moreover, it can be slowed down due to the manual process and because coordinators can react only to problems that have already occurred.

The `Smart Construction` platform aims to support the management and operation of a construction site, where numerous actors (e.g., vehicles, workers, drivers, project managers) need to cooperate in a synergistic manner by respecting their own workflows and procedures. The platform is able to deal with the dynamics of the scenario, in terms of both the variability of construction site procedures (e.g., highway construction, bridge construction) and the contextual changes affecting its operation. `Smart Construction` is able to provide techniques to dynamically instantiate different workflows and to specialize them in specific contexts [3, 11] by considering the different available resources. All the needed (contextual) information such as real-time data (e.g., truck speeds; bulldozers, trucks, and rollers status; fill material quantity at the construction zone) are matched with the selected construction site. If a problem is detected, a workflow adaptation [12] is initiated to propose alternative procedures to the involved actors.

Smart Construction Platform

This section is devoted to the presentation of the platform in all its parts. The platform consists of two main parts, an on-site IoT network deployed at the construction site built out of appropriate, configurable smart nodes and a backend cloud platform with its user interface. An overview of the high-level components and their connections is presented in Fig. 1.

On-Site IoT Network

On site, one or more IoT gateways are deployed to create a local radio network infrastructure similar to the concept of LoRa gateways as used, for example, in [13]. The network operates around the 868 MHz industrial, scientific, and medical (ISM) band, with its proprietary protocol implementation because of the regulations regarding the frequency spectrum management and the hardware restrictions.

The European Commission, through the European Conference of Postal and Telecommunications Administrations (CEPT) and the European Telecommunications Standards Institute (ETSI) [14], introduced restrictions for the fair use of the ISM bands by short-range devices. The spectrum access is restricted through the usage of a maximum value for the duty cycle (i.e., through the limitation of the maximum total transmission time over an hour, the maximum time of a single transmission and the minimum off time between two consecutive transmissions) or through the use of the Listen-Before-Talk (LBT) and Adaptive-Frequency-Agility (AFA) techniques. SigFox and LoRa protocols are based on the duty cycle restriction, which severely limits the maximum number of the sent packets and their sizes (e.g., SigFox allows a maximum of six 12-B uplink messages per hour).

There are a few reasons we have chosen the TI-802.15.4 stack over the more popular LoRa/Sigfox protocols:

- As a star network, LoRaWAN requires rather expensive gateways (~US$120) to operate and has very limited data rate when it comes to near-real-time performance. LoRa integrated circuits (ICs) can provide up to 300 kb/s (37.5 kb/s typical), while 802.15.4 can achieve up to 4 Mb/s (500 kb/s typical).
- A custom version of the 802.15.4 stack can be used to achieve mesh networking, and this will achieve better network performance.
- Sigfox has a very similar performance to LoRaWAN, and it operates on a subscription-based service model. Our intended test areas were rural zones that were not covered by the Sigfox network.
- Our IC of choice (CC1350) offers higher data rate and lower power consumption at a cost of slightly lower range (~3 km line of sight). As a comparison, the supply current of CC1350 is 24.4 mA at +14 dBm, while SX1276 (a LoRa transceiver) consumes 29 mA at +13 dBm.

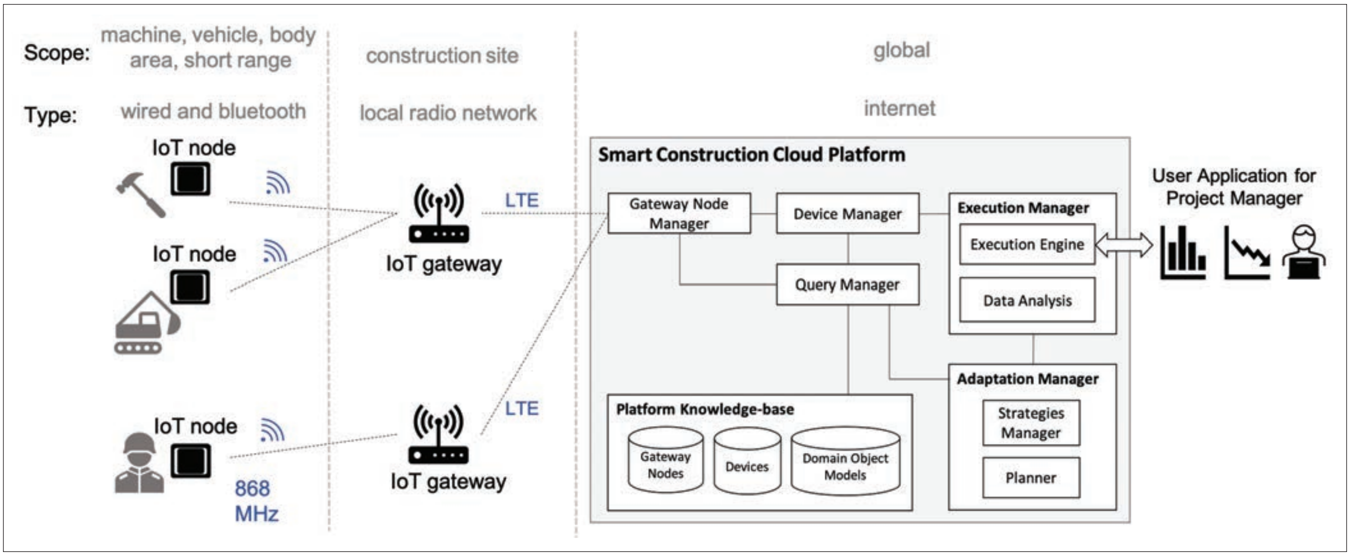


FIGURE 1. High-level technical overview of the `Smart Construction` platform. Smart hardware nodes distributed across the construction site collect and distribute information over the local radio network. With the help of IoT gateways, the system is connected to the cloud platform over the Internet (mobile or wired connection). Project managers can easily access the information remotely using the web-based user application.

All in all, LoRaWAN and Sigfox certainly have their application spots, and we are also considering them for a variety of other applications where real-time performance is not the main goal, but power consumption is.

The TI 15.4 stack used in this platform, developed by Texas Instruments and based on the physical and medium access control (MAC) layers defined by the IEEE 802.15.4 e/g standards, allows the usage of LBT and AFA through the already implemented functions included in its software development kit (SDK). The most recent version of the commonly known and broadly used Zigbee protocol, capable of using the 868 MHz band, has the same disadvantage as SigFox and LoRa [15], due to the fact that it is based on direct-sequence spread spectrum (DSSS) and not on frequency-hopping spread spectrum (FHSS) modulation. Additionally, the physical layer of the LoRa protocol is not publicly available, which restricts the range of usable radio modules.

The TI stack is compatible only with a few selected microcontrollers, but the range of options is broader, allowing, for example, a more powerful CPU including dual-band wireless chips. Tests with our nodes suggest an expected raw data rate around 50 kb/s, and they reach up to 4 km depending on the environment, the specific antenna setup, and the transmission power. This is sufficient for a high variety of use cases, and by deploying its own infrastructure, the system does not depend on the availability of mobile networks. However, the gateways are usually connected to the Internet through an LTE module, although this connection can also be realized by wired connection, for instance, via telephone cables or a satellite link, if necessary.

Emerging mobile technologies such as LTE-M and NB-IoT [16], might look promising for most of the use cases. However, these new technologies are still in their early adoption phase; thus, for remote areas with no cellular coverage, having a custom central gateway or multiple trees of gateways proves to be the best solution. On the other hand, for extremely low-power or battery-less applications, mobile communication is hard to implement due to the high transmission power requirements (~200 mA). Each LPWA technology has its own advantages and disadvantages, and there is no "one size fits all" solution [17]. In this case, our aim was to be independent of cellular coverage and achieve longer battery life. By using a proprietary radio solution, we achieved much lower transmission (~20 mA) and sleep currents (~1 μA).

On-site IoT gateways act as bridges between the construction site and the cloud platform. Smart nodes are distributed over the construction site, and they connect to the closest or the only available IoT gateway node, which will receive and relay the data packets to the cloud back-end. The gateways are also in charge of delivering data to the smart nodes from the platform, either as an answer to a request or as a trigger sent by the back-end services.

Configurable Smart Nodes

The realized configurable smart nodes are distributed over the construction site. They are attached to different vehicles, such as excavators and trucks hauling material. A functional overview of the smart nodes is shown in Fig. 2. By design, these nodes are highly configurable to adapt and evolve later on to different or more sophisticated use cases.

Power supply options include the use of external sources (e.g., onboard power of the vehicles), batteries, and energy harvesting (e.g., using solar panels). The combination of these sources is also supported by the board design, for example, by using the built-in battery to deal with gaps in the power supply when the vehicle is not used. A smart node can host many off-the-shelf sensors supporting a variety of protocols like I2C, SPI, and UART, and implementing the mikroBUS standard from MikroElektronika.[1] Examples for output modalities, instead, are a small LCD display for showing simple values and instructions, a buzzer for signaling notifications, or a tablet that can connect over Bluetooth Low Energy to the smart node and access the information available through the radio network. The core task of the smart nodes is sensor data acquisition. They regularly read available sensors' values (e.g., location, acceleration, idleness), pre-process and filter data, and send the values over the radio network to a gateway. They can also cache data locally when the radio connection is not available.

The star topology was selected since mesh networks add additional complexity and significant resource overhead, which is planned to be evaluated in future work. If nodes move out of reach of the gateway, they can cache data locally when the radio connection is not available.

A feature shared among all the smart nodes is their ability to join/leave the local radio network and communicate with the platform's components. This makes the construction site an *open* and *dynamic* environment where the availability/unavailability of devices and their functionalities is not known a priori (e.g., smart nodes with low battery can leave the network for a while). Thus, customization and adaptation are key features of our platform.

Cloud Platform

To deal with the openness and dynamics of construction sites, and to allow project managers to *remotely* manage multiple construction projects in different locations, we exploit specific approaches. More precisely, we make use of a *design for adaptation* approach proposed in [3] for the design and execution of dynamic user applications on top of the presented platform. The strength of the design for adaptation approach is twofold: (i) it allows independent and heterogeneous things (e.g., sensors, actuators) to be defined in a *uniform* way by means of the so-called *Domain Object* model; then (ii) it allows for the dynamic composition of things functionalities as well as services, to reach both application and user *goals* (i.e., monitor trucks' cycles and react accordingly). In different execution contexts (i.e., construction sites), the way a goal can be achieved can vary, since it can be provided by diverse devices due to the high degree of heterogeneity in IoT. Consequently, the possibility of abstracting the reasoning from the low-level interactions with devices is a strong requirement to provide customizable applications. The design for adaptation approach allows project managers to interact with and benefit from the on-site IoT in an effortless and transparent manner.[2]

Thus, the `Smart Construction` cloud platform contains components specifically acting as enablers of its easy customization. Thanks to this feature, our platform can execute applications for diverse construction sites where different types of civil engineering projects are running (e.g., highway, bridge, building).

In particular, Fig. 1 (right side) depicts the main components of the `Smart Construction` cloud platform with their connections. The *Gateway Node Manager* represents the access point to the platform. It is responsible for managing the gateway nodes distributed in the different construction sites. Each gateway node is previously registered in the platform *Gateway Nodes* database, as a tuple made by a key and a signature. The Gateway Node Manager also handles the gateway authentication during the execution phase by accepting information only from gateway nodes with a valid key-signature entry.

The platform holds its internal knowledge in three databases. The *Gateway Nodes* were just described. The *Devices* database stores information about devices (e.g., smart nodes) available at the different sites, such as the site id, the device state (e.g., turned on/off) and the device location (e.g., on the truck with a specific ID), and their measured data. The *Domain Object Models* database stores all the designed domain objects (i.e., the basic artifact of the design for adaptation approach) uniformly defining the on-site IoT devices, and the information about available capabilities they are offering.

The execution starts from a project manager running a specific application defined on top of the `Smart Construction` platform, such as that for managing the earthwork phase of highway construction. The project manager can easily switch from one highway construction site to another, also located in different cities, due to the possibility of customizing the specific application.

The *Execution Manager* component deals with the execution of the user application and the application of data analysis methods and techniques. The *Execution Engine* performs the execution of the abstract application process (i.e., workflow) and triggers the *Adaptation Manager* whenever an adaptation need arises (i.e., customization of an abstract workflow or a monitored parameter is out of its threshold). The *Data Analysis* components, instead, implements different data analysis and optimization algorithms allowing quick understanding from the current situation of the construction site the best adaptation strategy to apply (e.g., by monitoring specific parameters) if required. Moreover, Data Analysis can be triggered by both users, directly from their interface and by the Execution Engine, if it needs some reasoning on the data received by the devices at the construction site while executing the user application.

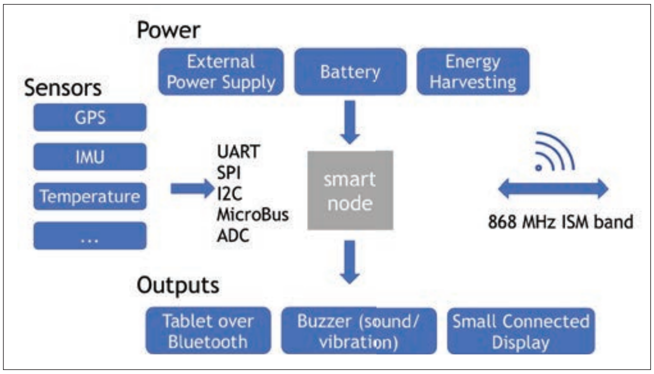


FIGURE 2. Functional graph of smart nodes: different sensors can be attached by a variety of hardware protocols; optional output modalities and power supply sources make the nodes customizable for a variety of use cases.

The *Adaptation Manager* deals with the customization and adaptation of the user application. The *Strategies Manager* implements different adaptation strategies to solve different needs. Given a specific adaptation need, it defines an adaptation problem by also identifying the devices whose functionalities can be exploited to solve the adaptation need [12]. To define the adaptation problem, it queries the Platform Knowledge-base component looking for the required devices and their corresponding domain object models at the current site. The adaptation problem is passed to the *Planner*, which is in charge of providing an adaptation solution in the form of an executable process, made by the composition of devices' functionalities, that can be injected in the running user application process.

The *Device Manager* component is responsible for answering queries coming from the Execution Engine about available devices, their state, and their sent data. Queries about the devices' status can also come by the Data Analysis, asking information to perform its reasoning. Then it is in charge of collecting and managing tasks about storing device data for the different construction sites through the Gateway Node Manager.

The *Query Manager* component implements an abstraction layer between the above described component services and the platform's databases. In this way, it provides a consistent data and knowledge management interface for the platform.

User Interface for Project Managers

The platform is meant for personnel responsible for the efficiency of the construction site for handling any upcoming issue. These are typically construction site managers and coordinators. To support them in making the right decisions, the platform gives them access to real-time information, notifications, and current and historical statistics remotely from a desktop computer or mobile device.

Two snapshots of our implementation of the *User Application Interface* can be seen in Figs. 3 and 4. They show dashboard excerpts, reporting up-to-date information about the construction site, and its progress and performance metrics.

The *User Application* component in Fig. 1 is responsible for loading a specific application process requested by the user and triggering its execution. Specifically, each user application is defined as an abstract process by abstracting the workflow of a specific civil project (e.g., highway construction). During the application process execution performed via dynamic and incremental IoT service composition [12], the process will be refined, step by step, through the addition of the IoT services provided by the real devices operating in the referring construction site.

FIGURE 3. Screenshot of the user interface dashboard: a real-time view of state, locations, and activities for each tracked vehicle helps the project manager to get an overview at a glance.

Implementation and Discussion

In this section, we give details about the realized platform. Each *Smart Node* is a custom designed board consisting of two submodules. At the heart of the node, we have a custom radio module, which is based on the Texas Instrument CC1350 dual-band IC supporting operation at 2.4 GHz and sub-1 GHz frequency bands. The module includes this chip and minimalistic supporting components. This module sits on top of a main board that carries various types of sensors, and power management and solar energy harvesting circuitry. We used a waterproof enclosure with a clear top and, in order to prolong the battery life, we integrated a 5 V; 0:6 W solar panel onto the transparent top. Normally, our smart nodes are placed flat on machinery, and depending on the current position and time of the day, the solar panels can produce up to 0:4 W, which greatly increases the battery life.

By using strong magnets at the bottom of the box, it can be quickly and easily attached onto the construction vehicles (e.g., on the arm of an excavator). Typically, these vehicles have large steel parts, providing us with plenty of possible placement options. In our experiments, four magnets (diameter of 17 mm) proved to be sufficient enough to keep the sensors in place during typical earth-works. Figure 5 shows attached smart nodes on an excavator's arm and on a truck.

The *gateway* of the platform consists of a special version of the smart node with an external antenna for better reception. It is programmed with modified firmware for robustly receiving transmitted data packets. This node is optimized for performance rather than power consumption and includes some additional network coordination functionalities. It is connected to a Raspberry Pi 3, running the default Raspbian operating system with custom bash scripts handling state restore in case of power outages. The gateway software itself is implemented in Python and has the main task of checking the consistency of the incoming data, enriching it with meta information (e.g., more accurate, global timestamps), and transmitting it to the cloud platform while caching everything locally in case the connection is down. For the connection to the cloud, we used a USB LTE modem from Huawei (e3372) equipped with a local SIM card and a data plan.

The *back-end* of the platform includes basic functionalities to be able to receive, store, and retrieve data. For that, we implemented a REST API with NodeJS, which was then packaged into a Docker container. Alongside this container, we also deployed a containerized version of the NoSQL database MongoDB on an Ubuntu virtual machine.

Concerning the *User Interface*, the users are able to follow the vehicles with their location, orientation, and current speed, and they can see measured temperature and activity at a glance. Furthermore, statistics like those in Figs. 6b, 6c, and 6d are displayed for visually inspecting the process characteristics.

Construction Site Tests

We performed two tests of `Smart Construction` on two real construction sites. The first was a highway construction site, where we equipped two trucks and one excavator referring to a specific transportation route and collected data over approximately two hours. The main goal of this test was to verify attributes of the system, such as transmission range, mounting principle, and data quality. The second test was performed at a site of a photo-voltaic power plant construction, where four trucks and two excavators were working on two different transportation routes. At this location, we collected sensor data from all four trucks and one of the excavators during a whole shift from 7 a.m. until 2 p.m.

For data inspection, we mainly used the collected data from the second construction site, although the data from the first site showed similar characteristics. A visual representation of the vehicle tracks on this construction site is displayed in Fig. 6a. Frequently traveled routes are clearly visible. The two variants of route 1 are on the upper right side, while route 2 is on the bottom left side.

Figure 6b shows the cycle durations for each truck over the morning shift. Trucks 1 and 4 were mainly on route 1, while trucks 2 and 3 were on route 2. On this timeline, an interesting observation is that longer cycle durations on a specific route are clustered together in time. If there is a delay for some reason on the route (e.g., an excavator has to adjust its position), the emerged delay is propagated over some cycles until the cycle durations settle down to normal again. These are the delays that our system targets to avoid when fully deployed on the site.

Distribution of the duration times per route is displayed in Fig. 6c, while the detailed breakdown of the duration times is in Fig. 6d. The different activity states of the vehicles are extract-

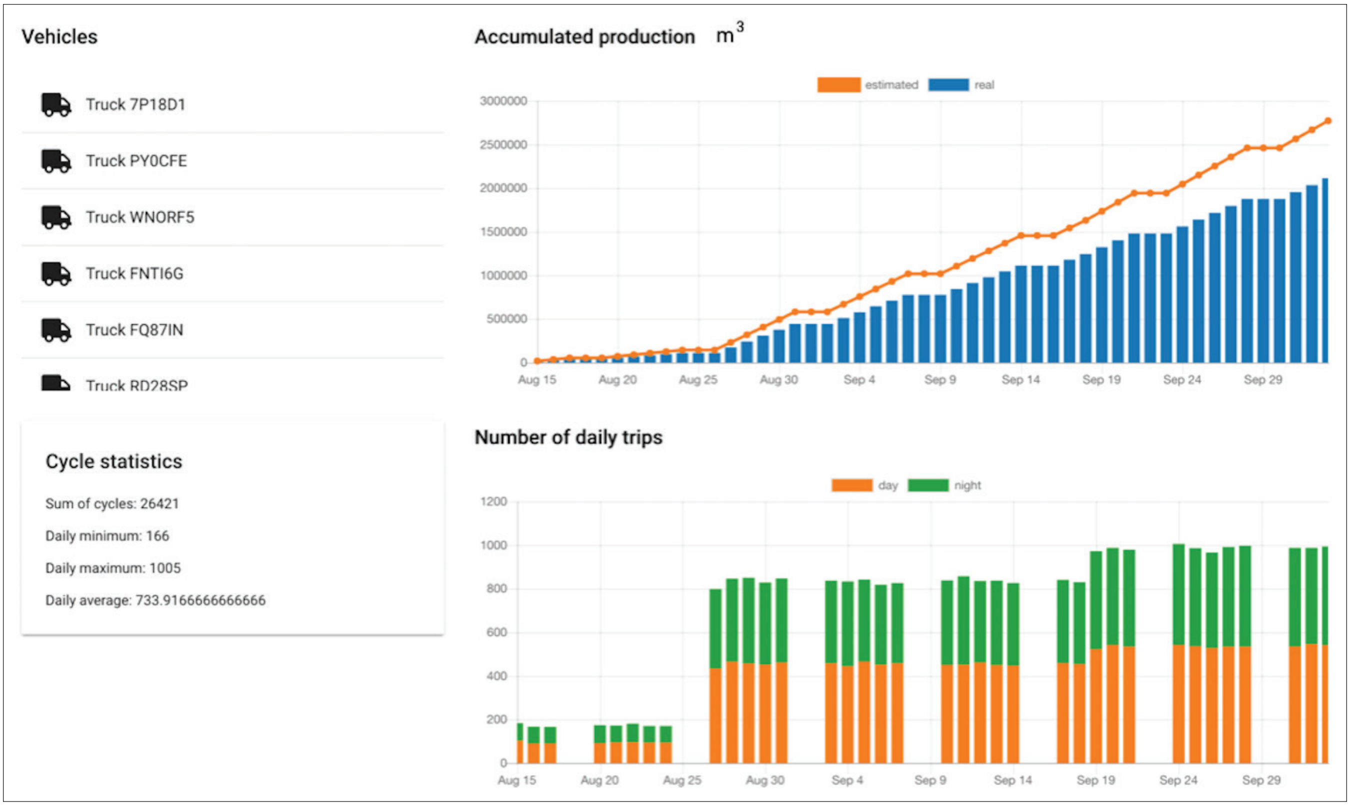


FIGURE 4. Screenshot of the user interface dashboard: historical production data and statistics over weeks, including number of cycles per shift per day and a graph for accumulated production with the corresponding target values. These data give helpful insights about the project.

ed automatically with a simple decision tree classifier after a short training phase using data like position and speed of the vehicles. Data can be visualized in real time, which otherwise is expensive to get and only after delay of hours or even days using traditional methods. These views help us and the project managers get useful insights about the running processes. Deviations from the norm (e.g., when hauling periods start taking more time on the same route as usual) can be intuitively recognized and analyzed (e.g., bigger vibrations on the way, deteriorated road quality) on the fly. Based on the easily available, comprehensible, and up-to-date information, project managers can initiate appropriate adjustments and adaptations (e.g., utilizing more vehicles or improving service road quality).

FIGURE 5. Left: picture of the smart node; right: smart nodes are mounted on the excavator and a truck; the locations are marked with white circles.

Lessons Learned

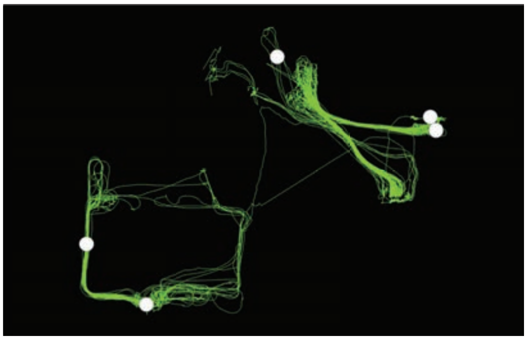
The intended goal of these first two construction site tests was to verify the technical parameters and feasibility of the proposed platform. The use of magnetic mounting and weather-proof housing for the smart nodes worked as expected without any problems over seven hours of normal work conditions. On both sites, we performed measurements of the transmission range of the radio communication at first. Antenna design is a very complex field of engineering, and the realized system definitely has room for improvement regarding this aspect. Nonetheless, the maximum transmission range we achieved was about 1.5 km on an fairly open field.

A critical observation is that the gateways (or, more specifically, their antennas) should not be placed inside container offices. These can act as a Faraday cage, blocking or significantly reducing the data transmission range between smart nodes and gateway nodes. For Internet connectivity, we tried different USB LTE sticks, which worked well with a local SIM card, but both of them failed to connect in roaming mode, although the used SIM card supported them.

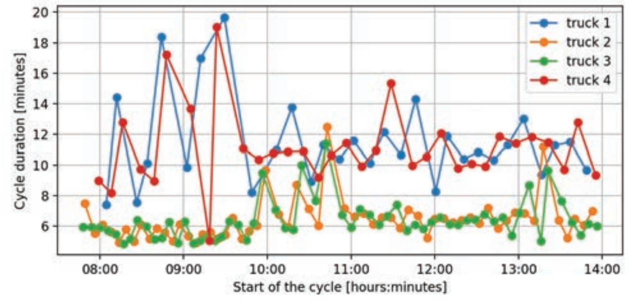
Besides this technical evaluation, discussion with experts in different professions on the construction site gave us essential insights and impulses for the further improvement of the platform. While the workers and project managers are generally curious and open minded about the opportunities of using new technologies, typically they are very pragmatic and practical people. They also reported the difficulties of overcoming a general lack of technology acceptance and adoption in the construction industry. Any system on which they are willing to invest time and money has to provide benefits for their work on a short-term basis. Long-term advantages are in fact important, but subjective priorities are shifting under pressure in competition for heavily restricted resources (budget and time). Another interesting topic brought up during conversations is the aspect of security. Construction sites cover large areas and cannot be protected everywhere at all times. Distributed resources of some value, such as gateway nodes, have to be equipped with some degree of protection against theft.

Conclusion and Future Works

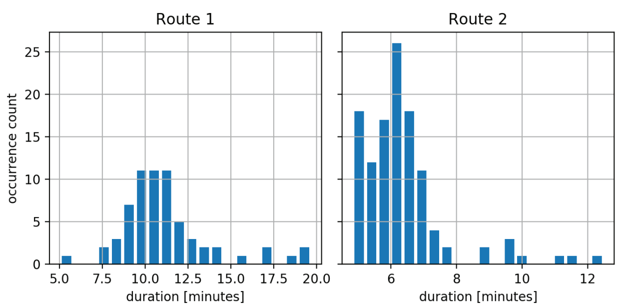
In this article we present `Smart Construction`, an IoT cloud-based platform aiming to digitize and improve processes of large civil engineering projects. In a first phase, our main



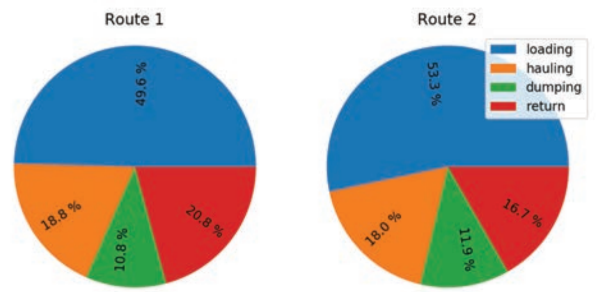
(a) GPS tracks of the vehicles over a workday



(b) Cycle duration for each truck during the morning shift. Trucks 1 and 4 were on route 1, while trucks 2 and 3 on route 2.



(c) Distribution of cycle durations on the different routes during one shift.



(d) Composition of cycle durations on the two routes. There are small differences between the routes, but in both cases around half of the cycle is spent in waiting for loading and with the loading process itself.

FIGURE 6. Construction site tests: collected data and performed analysis.

effort was focused on the development of the smart nodes, the main interface to the reality at the construction site. In a second phase, instead, we focused on the modeling of customizable applications addressed to the platform users (e.g., project managers) through the exploitation of a design for an adaptation approach. This way, users can remotely monitor different construction sites by getting up-to-date information used to trigger a dynamic adaptation of the running projects' processes. The `Smart Construction` platform has been validated by testing it on two real highway construction sites.

This setup was flexible and sufficient for the initial tests. In future work, we plan to adopt the system for utilizing the existing IoT framework, such as for device management, described previously.

Based on the lessons learned during on-site tests, our next iteration will focus on improving the gateway implementation and range enhancements of the radio network (e.g. by implementing and evaluating different mesh approaches). Our future goals are to deploy the system for longer time periods by using an improved on-site IoT network, and to train and evaluate analytics and optimization models by using the new larger dataset and exploiting new ways to collect them [20]. From the user application side, we will focus on data processing, for example, by implementing machine learning algorithms and measures to quantify the value gain in the holistic context of complex construction project structures. This also includes exploration of other processes of the construction industry, where the proposed platform can provide a significant step toward the vision of a fully digitized process management and control.

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