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IoT-altimeter in smart pallets for material tracking on multi-storey construction sites

Maximilian Gehring*, Jens Wala and Uwe Rüppel

Department of Civil and Environmental Engineering, Institute of Numerical Methods and Informatics in Civil Engineering, Darmstadt, Germany

* Correspondence author; E-mail: gehring@iib.tu-darmstadt.de.

Highlights:

- An IoT-based material tracking system was developed.
- A height measurement functionality was implemented using digital altimeters.
- Transmission of the captured data is achieved via LoRaWAN.
- The height detection accuracy and LoRaWAN signal strength inside buildings were evaluated.
- A demonstrator setup was designed and built.

Abstract: The efficient localisation of building materials on construction sites is a key challenge in the construction industry. Especially in multi-storey buildings, the manual search for materials leads to time losses and increased costs. This paper presents an IoT-based material tracking system based on barometric sensors and LoRaWAN communication. By utilising digital altimeters, the height of the material is determined, allowing it to be assigned to specific floors. A demonstrator was developed to analyse the feasibility. It shows the potential of the system for optimising material tracking on construction sites. Future work should focus on field tests in real construction site environments in order to evaluate its suitability for practical use. In addition, optimisations in terms of measurement synchronisation, energy efficiency and signal coverage are required to enable widespread use in complex construction projects.

Keywords: construction logistics; IoT; material tracking; LoRaWAN

1. Introduction

One of the tasks of construction logistics is to organise and monitor the flow of materials on the construction site [1]. Due to the limited central storage options on a construction site, the building materials delivered are usually distributed decentrally. This leads to a lack of overview of the material stored on the construction site [2]. As a result, workers on the construction site spend up to a third of their working time searching for materials and tools and making unnecessary movements on the construction site [3,4]. Against the backdrop of rising costs and a shortage of skilled labour, it is necessary to increase the efficiency of workers on the construction site. Construction logistics is therefore an important factor in the successful realisation of construction projects and increasing efficiency [5]. Developments relating to the Internet of Things (IoT), *i.e.* new wireless standards, the miniaturisation of electronic circuits and the reduction of the energy requirements of electronic circuits, make it possible to track and monitor objects using networked sensors [6]. Approaches to material tracking already exist, particularly in stationary industry and basic logistics [7]. So-called smart pallets are also used there. Smart pallets are transport aids equipped with various sensors that allow, among other things, the monitoring of loading conditions and the tracking of the transport aid [8]. Due to the specific characteristics of construction logistics, the existing approaches cannot be transferred directly [1]:

- Due to the nature of the project, fixed installations such as antennas for radio localisation or optical markers are not technically possible and not economical.
- As material flows are exposed to the weather and other mechanical influences, markings or stickers on surfaces are quickly destroyed or no longer legible.
- The limited storage capacities on construction sites are usually spread over several floors or over a wide area.

As a result, existing solutions for material tracking are often impractical and new systems need to be developed. Above all, such a system should be cost-effective in terms of procurement and operation and require minimal installation effort [9]. Due to the complexity of the problem, this paper examines a material tracking system specifically for construction sites with multi-storey buildings. For this purpose, it is proposed to equip smart pallets with IoT altimeters. This results in the following research question:

RQ: Are IoT altimeters suitable for material tracking on construction sites with multi-storey buildings?

To answer the research question, developments in the field of construction logistics, IoT related wireless technologies and material tracking approaches are first analysed in more detail. Furthermore, terms and requirements are defined. A concept for a system for material tracking on construction sites with multi-storey buildings based on smart transport aids equipped with barometric sensors is then designed. Several series of tests are then carried out to determine the suitability of the technology used for tracking and a demonstrator is presented. Finally, the concept is evaluated on the basis of the test series and further development steps are identified.

2. Research design

In this paper, a developed concept is analysed with regard to its feasibility. Such confirmatory research work is also referred to as an experiment [10]. An experiment has 4 phases:

(1) Definition of the variables
(2) Setting up the hypothesis
(3) Design of experiments
(4) Measuring the variables

Chapter 3 therefore describes the requirements and boundary conditions. In chapter 4, the variables are further narrowed down and the central hypothesis is formulated: ‘Barometric sensors in smart pallets with LPWAN (low power wide area network) are suitable for material tracking in multi-storey buildings.’

Chapter 5 then describes the experimental setup used to test the hypothesis and the technology used. The measured values are also presented and analysed.

3. Background

3.1. Construction logistics

Construction logistics deals with the control and organisation of material and information flows for the successful implementation of construction projects [1]. It is an essential part of the construction process and includes the supply of construction sites with the necessary building materials, the disposal of waste and the transport of materials and waste to the construction site. The specific characteristics of the respective construction site are decisive for the logistical challenges [11].

Construction sites, also known as work sites, are located at the site of the future building and are to be regarded as temporary production facilities specifically specified by the client [12]. In principle, a distinction can be made between fixed and mobile work sites. The categorisation of a construction site into these categories has a considerable influence on the logistical processes. A distinction is also made between horizontal and vertical construction sites [13]. Vertical construction sites, especially in building construction, are more complex as they require a large number of players and complex coordination of material flows between different floors. This makes detailed logistical planning essential. The volume of materials varies greatly between different types of construction. While large components in particular are transported and installed in civil engineering, there is a significantly higher number of active trades and material deliveries in building construction, especially in finishing work [1]. Complex technical construction processes should also be considered in detail in order to manage the increasing complexity through coordinated logistics approaches. A specific feature of linear construction sites is the repetition of identical work processes in fixed sections. The same activities are carried out in several areas of a construction site, resulting in recurring logistical requirements.

Construction logistics comprises various sub-areas that need to be differentiated in terms of their function. These include supply logistics, disposal logistics and site logistics (see Figure 1) [3]. The focus of this paper lies on the site logistics, where material and waste is moved between the floors of a building within the boundaries of a construction site.

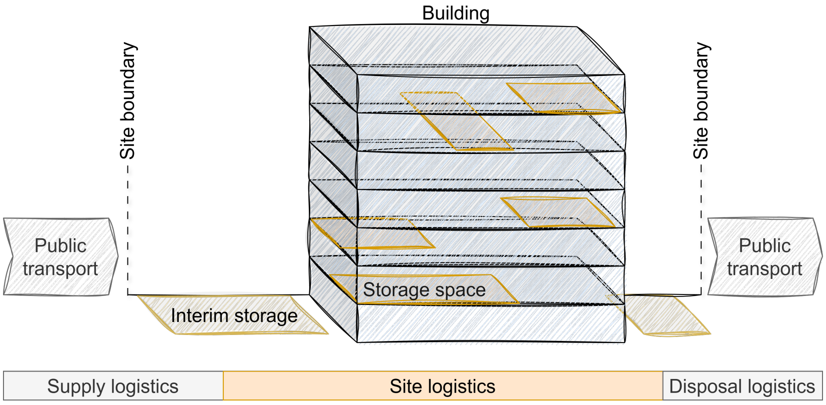


Figure 1. Areas of construction logistics (based on [3]).

Inefficient construction site management can lead to considerable problems. Insufficient material stocks, ineffective warehouse organisation and long search times result in increased costs and reduced productivity [14]. The inadequate documentation of material storage on construction sites poses a particular challenge [15]. Effective construction site management requires continuous monitoring of the actual position and quantity of materials on the construction site. Deviations from the original planning can be caused by human error, deliberate changes or unforeseeable environmental influences. Precise recording and control of these resources is therefore essential. This paper focuses on the construction logistics of vertical building construction projects, in particular multi-storey buildings. These projects are characterised by specific challenges in material distribution, storage and coordination, since the material stored is spread over several floors and a specific management of the material flow within the building is required.

3.2. *IoT and related wireless technologies*

The Internet of Things (IoT) describes a network of physical, everyday objects that are not otherwise considered digital objects, with computing capabilities [16]. These objects are equipped with sensors, software and other technologies to collect, process and exchange data with each other or with centralised systems [6]. The wireless technologies used include WLAN, Bluetooth or Bluetooth Low Energy (BLE), WPAN (e.g. ZigBee), LPWANs (e.g. LoRaWAN), RFID, UWB and 4G/5G.

- ZigBee is a Wireless Personal Area Network (WPAN). It is a network specification for applications with low power consumption and data volume. The devices communicate in a mesh network, which is why the network is particularly fail-safe [17].
- WLAN (Wireless Local Area Network) is a radio network with greater transmission power and range than WPAN. It is standardised by IEEE 802.11. The marketing term is WiFi [18].
- BLE (Bluetooth Low Energy) is a wireless technology that can be used to network devices at close range. Compared to classic Bluetooth, BLE enables lower power consumption and is therefore more suitable for IoT devices [19].
- LoRaWAN (Long Range Wide Area Network): is a low power wide area network (LPWAN). It was developed by the LoRa Alliance. Due to the longer wavelength, it offers better component penetration and a greater signal range. The disadvantage is the comparatively low data rate [20].
- RFID (Radio Frequency Identification) systems consist of tags and receivers, which usually only exchange the tag's identification number. Passive RFID tags have a range of around 2 metres, while active tags can cover distances of up to 100 metres [4].
- UWB (ultra-wideband) is a short-range RF technology. This technology is characterised by a high transmission rate and very precise localisation accuracy [21].
- Cellular technology refers to mobile communication standards such as 2G, 3G, 4G (LTE) and 5G. These technologies enable wide-area network coverage and high data transmission rates. They are suitable for IoT applications that require mobility and reliable connectivity over long distances. However, they typically involve higher energy consumption and operating costs compared to other wireless technologies [22].

The different wireless technologies are evaluated based on their range in an urban environment, energy requirements and data transmission rate (see [4,23–26]). A tabular overview of these parameters is shown in table 1.

Table 1. Characteristics of IoT wireless technologies [4,23–26].

	WLAN	BLE	ZigBee	LoRa-WAN	RFID	UWB	4G
Range (m)	250	100	100/1.000	10.000	2/100	10	10.000–35.000
Bitrate (Mbit/s)	288,8	25	0,25	0,05	1670	460	50
Energy demand	High	Low	Low	Very Low	Low	High	High
Frequency (MHz)	2.400/5.000	2.400	2.400	433–923	860–960	3.100–10.600	800–2.600

A key factor for the suitability of a technology in indoor applications is building penetration. There are major differences between the technologies here. Most of the technologies are unsuitable for the highly variable environment of a construction site due to its low building penetration, requiring a dense network of transmitters and receivers. LoRaWAN, however, offers high penetration due to its low frequency, as it is evaluated by Muzammir *et al.* [27] and Saban *et al.* [28] in indoor environments. This allows an implementation with a low infrastructure threshold. GNSS (Global Navigation Satellite Systems), e.g. GPS (Global Positioning System), is also used for positioning. However, this technology is not suitable for indoor applications due to its insufficient accuracy (around 5 metres) and poor component penetration [4].

A key criterion for assessing wireless technologies is the quality of the received signal. Two parameters are decisive here:

- Received Signal Strength Indicator (RSSI): This value indicates the received signal strength and is used to assess the connection quality. RSSI is a useful metric for troubleshooting wireless problems and is measured in dBm. The closer the value is to 0, the better the signal strength.
- Signal-to-Noise Ratio (SNR): The ratio between the useful signal and the noise level influences the transmission quality and stability. SNR is calculated by dividing the power of the received signal by the power of the noise. It is measured in dB. A higher SNR value indicates a better signal.

Both parameters are essential for optimising IoT networks, especially in challenging environments like construction sites with high interference or long distances. For extremely dense deployment areas, a hybrid communication approach is advantageous. Critical or low-latency data may be transmitted via local Wi-Fi or 5G, low-rate telemetry through LoRaWAN under duty-cycle constraints, and short-range identification via BLE or UWB. By distributing tasks across technologies according to their strengths, the load on any single wireless system is reduced, enhancing reliability and scalability in complex environments [29].

3.3. Material tracking

Material tracking describes the real-time monitoring and management of materials within the supply chain [30]. The aim of this technology is to improve production quality, production processes and logistics services [31]. By recording and managing material flows more precisely, inefficiencies can be reduced and work processes optimised. A key benefit of material tracking is the increase in work efficiency. By reducing unnecessary search times and minimising time-consuming manual administration processes in material warehouses, the workload can be significantly reduced. A case study by Grau *et al.* [32], for example, showed that the use of material tracking increased efficiency by 4%.

Various approaches to material tracking have been developed in logistics and construction logistics in particular. Originally, tracking was based on manual processes, which involved a considerable amount of labour [32]. With digitalisation, however, automated solutions have become increasingly established, enabling more accurate and efficient material tracking. The digital systems include simple technologies such as QR codes, which were developed by Peltokorpi *et al.* [33] have investigated. In addition, various radio-based and visual tracking technologies have been developed:

- Radio-based technologies:
  - RFID [2]
  - ZigBee [34]
  - LoRa and BLE [4]
  - BLE [35]
  - GPS-supported localisation and UWB [36]
  - Combination of RFID and UWB for greater precision [37]
- Alternative approaches:
  - Visual detection using drone and camera systems in conjunction with computer vision [38,39]
  - Detection of movements using IMU-based (Inertial Measurement Unit) sensors [40]

Although various material tracking technologies have been developed, many existing approaches have significant limitations. However, visual systems can fail under certain conditions, such as poor lighting or complex environments. Motion detection systems are prone to drift and require regular initialisation and recalibration [36]. A key problem with wireless technologies is their cost-effectiveness: many of the available systems are too expensive for widespread use in practice [1]. In addition, the increasing number of IoT devices leads to increased radio noise and interference, which can impair the accuracy of localisation [25]. Furthermore, the installation of complex sensor systems is usually complex and involves considerable costs. Many of the solutions developed also have insufficient reliability and are often only suitable for specific applications. These challenges highlight the existing need for research in the field of efficient and cost-effective material tracking.

4. IoT-altimeter enabled smart pallet system

4.1. Concept

As existing approaches to material tracking are currently impractical, a new concept for tracking material on construction sites for multi-storey buildings has been developed. Above all, the approach should be cost-effective, require little installation effort and function reliably. It should overcome existing hurdles for practical use.

This gave rise to the idea of using smart pallets to track material flows on construction sites with multi-storey buildings (see Figure 2). The sensors in the pallet should enable the pallet to be assigned to a floor. To transmit the pallet information to a server for data analysis and information provision via a local wireless network, a local base station is required. A solution that does not require an additional base station, e.g. through the use of cellular technology, was rejected because the energy requirements and recurring operating costs are higher. In addition, the base station simplifies the calibration of the sensors on the pallets by providing a calibration pressure.

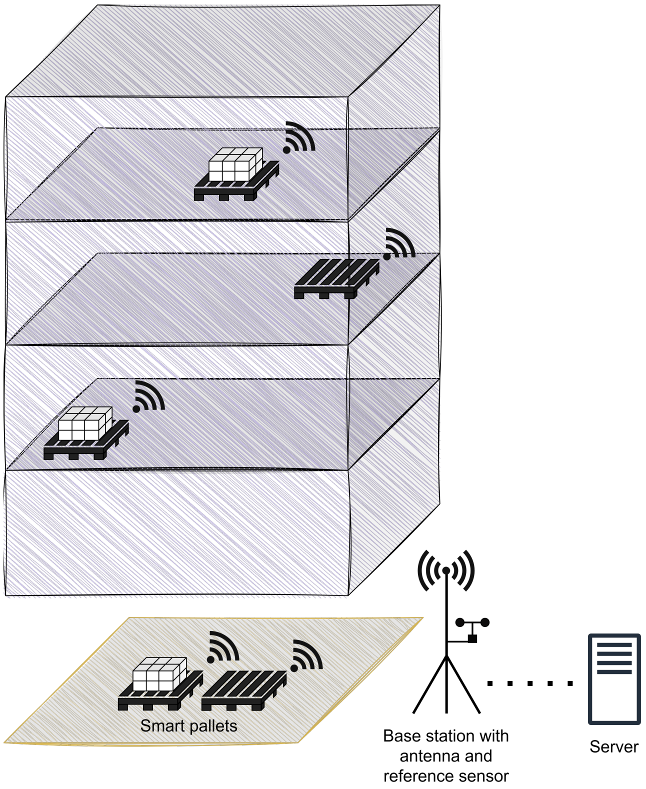


Figure 2. Concept.

In order to be able to assign the pallet to a floor, the height of the pallet is determined using barometric sensors. As the air pressure decreases with increasing altitude, the altitude can be calculated using the air pressure (see Figure 3). In the field of smart wearables, there are already approaches for tracking activities using barometric sensors [41]. They are also used to determine the altitude of flying objects [42]. In smart pallets barometric sensors together with temperature and humidity sensors are sometimes installed, but so far they have been used to monitor external influences on the transported material. The use of barometric sensors to measure the position of pallets in multi-storey buildings is therefore a special feature of the developed concept. The relationship between altitude and barometric pressure is described by the barometric altitude formula. By converting this formula, the altitude h (in metres) can be calculated using a measured barometric pressure P (in hPa) [43]:

$$h = \frac{T_0}{L}\left(1 - \left(\frac{P}{P_0}\right)^{\frac{RL}{gM}}\right) \tag{1}$$

The variables and the values used for U.S. Standard Atmosphere are shown below:

T_0 = standard temperature at sea level (288.15 K)
L = temperature lapse rate (0.0065 $\frac{K}{m}$)
P_0 = sea-level pressure
R = universal gas constant (8.314 $\frac{J}{mol*K}$)
g = gravitational acceleration (9.80665 $\frac{m}{s^2}$)
M = molar mass of Earth's air (0.0289644 $\frac{kg}{mol}$)

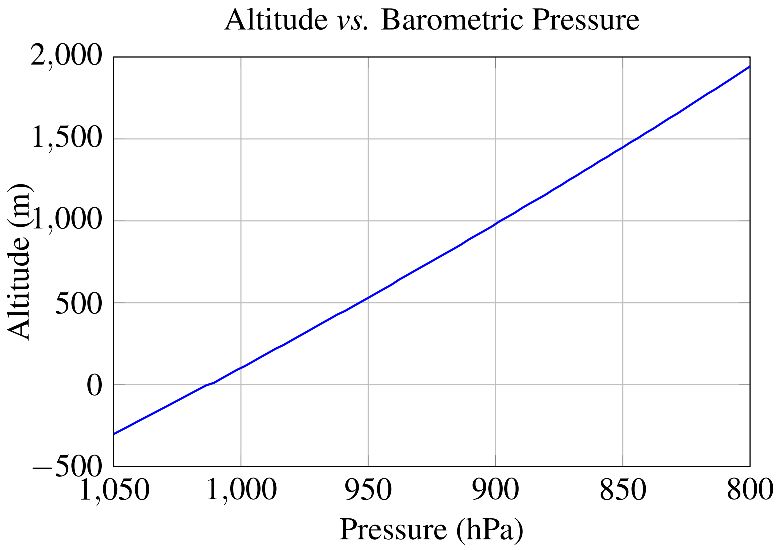


Figure 3. Altitude as a function of barometric pressure.

Using a measured barometric pressure P at time t and the sea-level pressure P_0 at time t, the altitude h of an object can be determined. To record the air pressure at the height of the pallet, standard Euro pallets (EPAL) [44] are equipped with a sensor box (see Figure 4b). This sensor box contains a digital barometric sensor and a LoRa-enabled microprocessor (see Figure 4a). This makes it possible to analyse air pressure data and transmit the sensor data to a central server. This creates smart pallets that can be used for material tracking. A calibrated base station with a fixed altitude on the construction site is required to measure the sea-level pressure. With a barometric sensor, such a base station serves as a reference point for categorising the measurements of the sensors on the smart pallets.


(a) (b)

Figure 4. Smart pallet system. **(a)** Sensor box with barometric sensor, microprocessor with LoRa antenna and battery pack; **(b)** Smart pallet (Euro pallet with white sensor box).

LoRaWAN technology is to be used for data transmission. The use of LoRaWAN ensures low energy requirements and good coverage and component penetration (as already explained in section 3.2. Although the data rate of LoRaWAN is low compared to other technologies, it is sufficient for the intended use case and sensor configuration. Only the measured pressure is transferred as a 4-byte payload. Real-time data transmission in this case would be described as an arrangement that allows the underlying process to occur normally, *i.e.* the materials on the construction site are not moved every minute. The system does not meet a strict definition (update every second), but this is not required either. This poses no limitation on integration of downstream tooling, like BIM or construction management software. The radio technology used is called LoRa. In some cities, good LoRa coverage is already available and can be viewed on a website [45]. Nevertheless, to ensure coverage of the construction site, a LoRa gateway should be attached to the base station on the construction site. To avoid noise and inference in dense IoT environments a mix of various protocol features, deployment strategies and ongoing monitoring can be used: On construction sites, meticulous planning of gateway locations and traffic patterns is the most effective way to ensure that interference is kept manageable. The initial configuration should comprise two to three gateways: one external (e.g. crane or roof) and one mid-stack. In cases where slabs are dense, it may be advisable to add a second indoor gateway near the top. It is anticipated that the addition of approximately one gateway per eight to ten additional floors in challenging structures will be necessary. It is imperative to minimise the length of vertical penetration paths, and to assign priority to the principle of line-of-sight through shafts and voids, as opposed to the endeavour to penetrate more than ten slabs. In the case of floors containing substantial rebar or mechanical rooms, it is recommended that a gateway be mounted on the relevant floor (or ± 1 floor) in order to localise traffic. Furthermore, the traffic patterns need to be planned: Use multiple gateways, time distribution of traffic and spread the traffic over available channels, frequencies and spreading factors.

The data collected from the construction site is dispatched to a server, where it is utilised to allocate pallets to a designated building floor. The communication of this information to site personnel is achieved through the utilisation of a user interface. This approach facilitates the integration of smart pallets within the material supply chain of a construction site, thereby enabling a more transparent and efficient exchange of information regarding the location and status of materials. Conventionally, the process of locating stored materials on multi-storey construction sites has been known to be time-consuming and to rely heavily on the memory of individual workers. The utilisation of smart pallets facilitates the automation of this process by means of continuous tracking of materials.

This spatial transparency has multiple benefits for the construction supply chain: deliveries can be confirmed and verified based on position data, the coordination between trades is improved by ensuring that materials are available at the right place and time, and bottlenecks in material flow can be detected early. Furthermore, historical data can be used to identify inefficiencies and optimise future material handling strategies.

By integrating the smart pallet system with existing construction site logistics (e.g. delivery schedules, BIM models, or inventory management systems), the system supports a digital twin of the construction site. This paves the way for a more connected and responsive construction supply chain that adapts dynamically to the progress on site.

5. Demonstrative implementation

The practical testing of the developed concept was carried out through a series of targeted experiments. Both technical and economic aspects were considered. The investigations included the accuracy of the digital, barometric sensors, analysing the signal strength of the radio technology used and building a prototype of the smart pallet. The prototype was used to evaluate the energy consumption of the sensor technology, the integration of sensors and microprocessors, the construction costs and the scalability of the system. The aim of these investigations is to validate the technical feasibility and economic viability of the material tracking approach using barometric sensors and LoRaWAN.

5.1. Accuracy of the digital barometric sensors

In order to verify the precision of the barometric sensors and assess their applicability to the specified use case, a series of experiments were conducted. In the initial experiment, the accuracy of the barometric sensors was subjected to a comprehensive evaluation through a prolonged test that spanned twelve days. In the period spanning 12/02/2025, 14:30 to 24/02/2025, 14:30, the sensors systematically measured the air pressure within an office building at two-minute intervals. The test setup consisted of two BMP180 sensors. Although Bosch no longer officially manufactures these sensors, they can still be purchased from independent manufacturers. In the long term, the BMP180 can be replaced by a similar sensor with a similar accuracy of $\pm$ 12 Pa, e.g. the BMP390, which is currently produced by Bosch. The test setup was situated at an elevation of 172 metres above sea level, with a disparity in height of 1.5 metres separating the two sensors (see Figure 5).

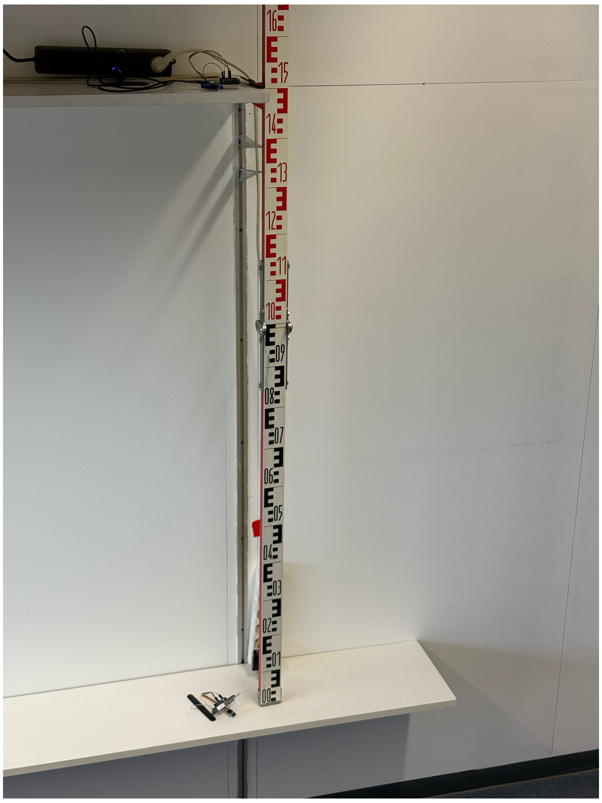


Figure 5. Test setup for long-term evaluation of the accuracy of the digital barometric sensors.

The barometric pressure data recorded by two sensors (*i.e.* 'smartpallet-01' and 'smartpallet-02') was analysed, along with the difference between the two measurements, over the course of the entire period (see Figure 6). At the beginning of the measurement period, for a brief interval, no significant pressure difference was measured between the sensors. A detailed evaluation revealed that this issue arises from the lack of synchronization between the measurement times of the sensors. Due to the temporal variations in the measurements (ΔT of up to one minute), the measurement curves were found to be superimposed on the occurrence of sudden and steep changes in air pressure. During periods of rapid pressure changes, such as those observed in storms, the synchronisation-induced error is approximately 0.17 *hPa*. This results in a relative synchronisation error of 94% (assuming a pressure difference of 0.17 *hPa* between 172 *m* and 173.5 *m* above sea-level).

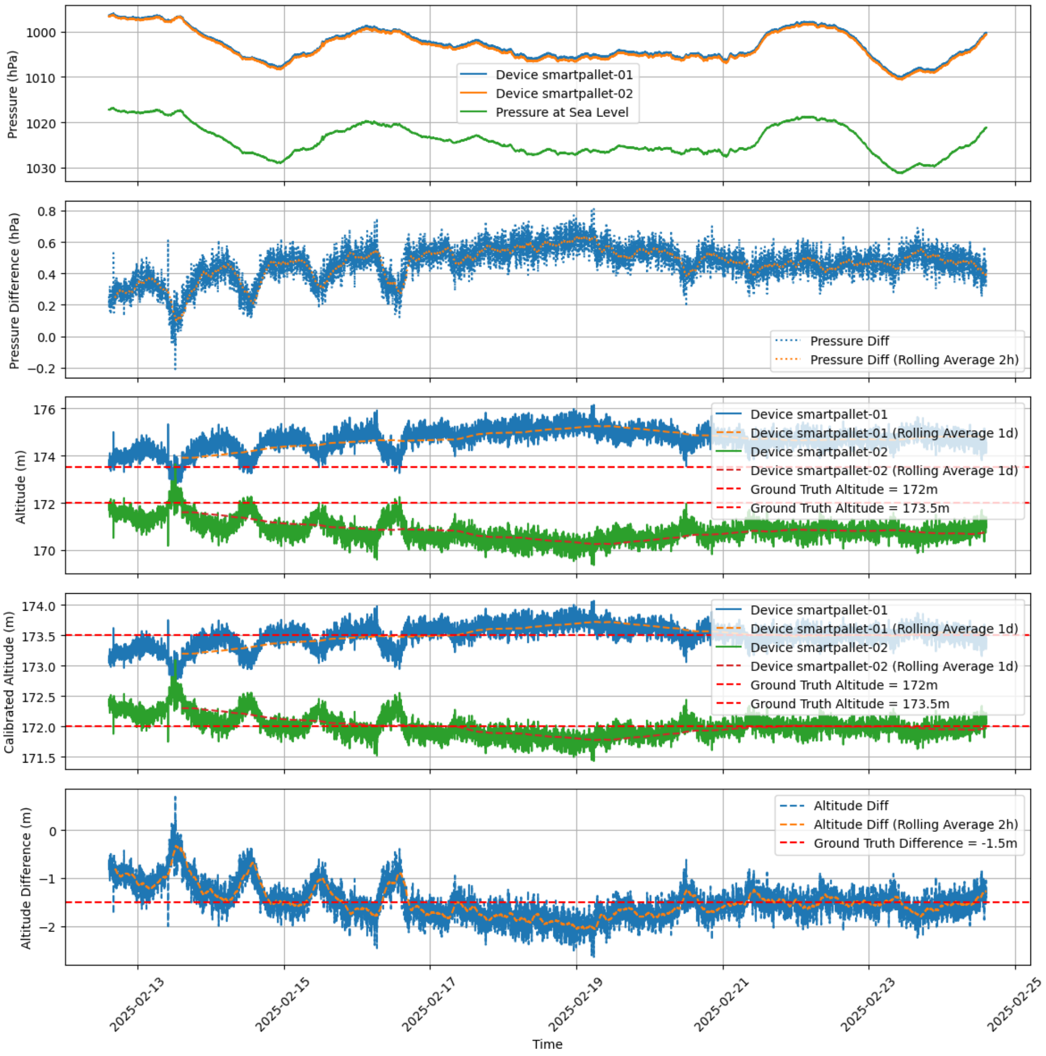


Figure 6. Measured values during long-term assessment of the digital barometric sensors.

Additionally, the height of the sensors was calculated based on the formula presented in section 4. Knowing the true height of the sensors, the calculation was calibrated. The resulting altitude and height difference is also displayed in Figure 6 to assess the stability and accuracy of the measurements.

The calibration of the sensors, in conjunction with additional filtering procedures designed to reduce noise in the measured values (e.g. a moving average), has been demonstrated to enhance the stability of the height measurement. It was observed that even a minor discrepancy in height, measuring a difference of only 1.5 m between the sensors, could be reliably identified over an extended period. The mean discrepancy from the true height value was approximately 0.2 metres. Consequently, the identification of a specific floor within a building, which typically possesses floor heights ranging from 3 to 4 metres, can be determined at any given moment.

In a subsequent experiment, the smart pallet demonstrator was transported within a building. A series of nine measurements were conducted on the smart pallet (see Figure 7). The pallet was moved along and between the floors of an office building. The recorded air pressure of the relocated device (smartpallet-02) and a stationary device (smartpallet-01) is displayed. Utilising the calibration data from the initial experiment, the position of the devices could be allocated to particular levels within the building (see Figure 8). The calculated height, indicated by the orange and blue 'plus' sign, is then compared with the actual level, symbolised by the red cross. This demonstrates the technical feasibility of the smart pallet concept for use in multi-storey buildings in order to facilitate the precise tracking of materials.

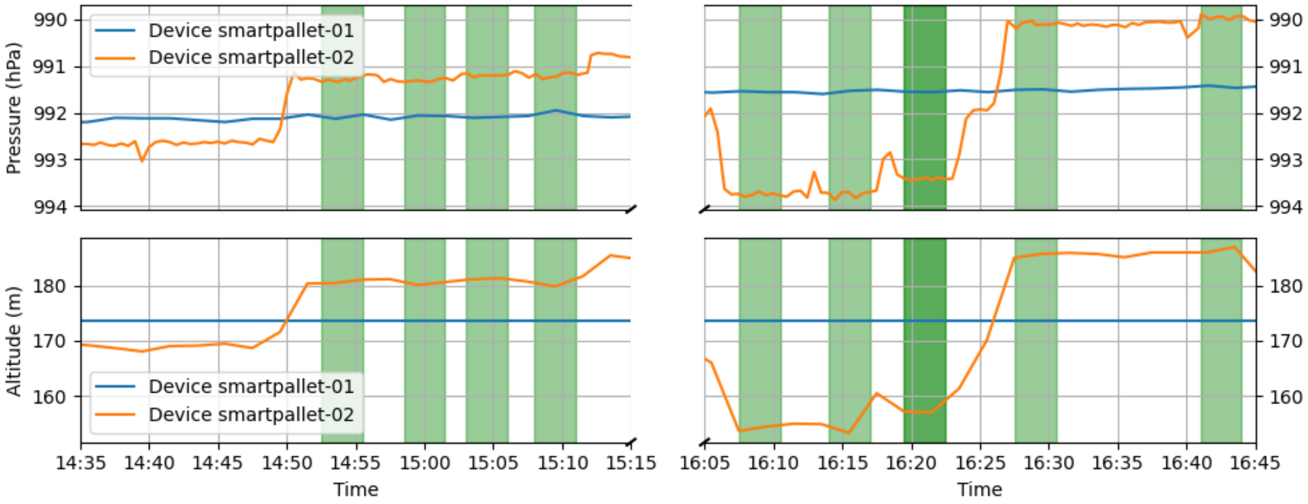


Figure 7. Measured values during applicability assessment of the smart pallet demonstrator.

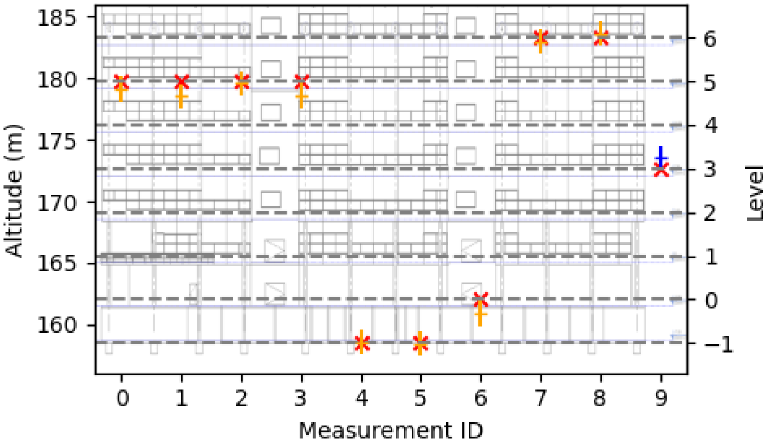


Figure 8. Assignment of smart pallet measurements to building floors.

5.2. *Analysing the signal strength of the used LoRa equipment in buildings*

In the course of the applicability assessment, the signal strength of the LoRa device was measured at the LoRa gateway during nine measurement periods (see Figure 9). This assessment involved the transportation of the smart pallet demonstrator within a building. The building has a floor area of 50 m (east-west direction) × 20 m (north-south direction) and comprises six floors and two basements. The aim of the investigation was to assess the coverage and signal quality within the building and the ability to reliably receive sensor data from different areas.

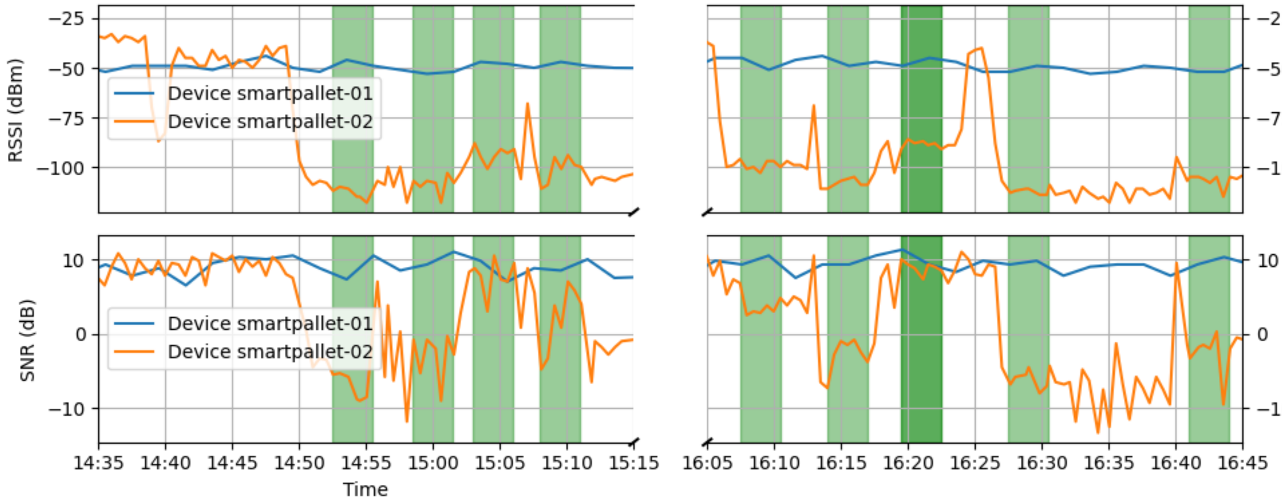
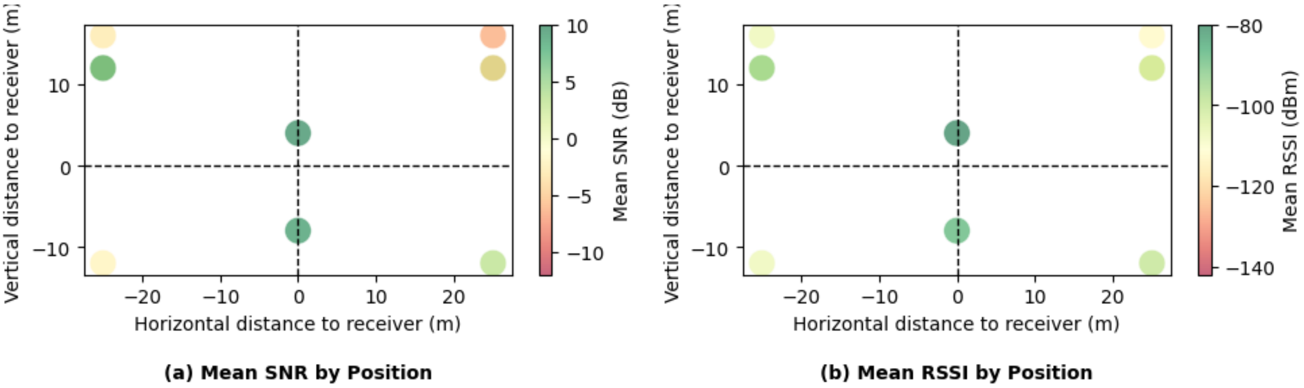


Figure 9. Signal strength during applicability assessment of the smart pallet demonstrator.

As a test setup, a LoRa receiver or gateway was positioned on the second floor in the centre of the north side of the building. A RAK7258 LoRa gateway with an external antenna was used. An Arduino MKR WAN 1300 with a dipole pentaband antenna and a BMP180 sensor was used as the sensor unit. The frequency plan used corresponded to the European standard (863–870 MHz) with spreading factor SF9. In order to systematically record the signal strength in the building, the sensor box or smart pallet was placed in different areas of the building over a defined period of time. The signal strength (RSSI) and signal quality (SNR) were recorded at each location (see section 3.2). The respective measurement ranges are labelled as green sections in Figure 9.

Exactly nine transmissions were carried out during each measurement period. No packages were lost resulting in a 0% package loss rate. The mean signal values of all nine transmissions were then calculated to assess the stability of the signal transmission. As illustrated in Figure 10, the signal strength (RSSI) and the signal quality (SNR) are represented by a colour code, with green indicating a good signal and red indicating a poor signal. The limits for receiving LoRa signals depend on the hardware and signal used. For the devices and signal properties used in the experiment, an RSSI limit of -142 dBm and an SNR limit of -12.5 dB apply [46]. A signal that falls below one of these limits can no longer be decoded. The analysis showed that a weakening of the signal could be observed in the more distant corners of the building, but the signal coverage and quality proved to be sufficient to ensure reliable data transmission.



(a) Mean SNR by Position **(b) Mean RSSI by Position**

Figure 10. Evaluation of the signal strength measurements.

5.3. Smart pallet prototype

A prototype of the smart pallet was built (see Figure 4). The central component of this system is the sensor box, which comprises various hardware components to enable reliable detection of height changes and wireless data transmission via LoRaWAN.

The sensor box consists of a 3D-printed housing made of 300 g white PLA at a cost of around €6. The barometric sensor used is a BMP180 from Bosch. This sensor has a very low energy requirement, a low measurement noise of 0.25 m and can communicate via an I2C interface. It is available for €1 to €2. Processing and communication are handled by an Arduino MKR WAN 1300 with an integrated LoRa module, the price of which varies between €20 and €40 depending on the source of supply. Power is supplied by a 1000 mAh Li-Ion battery for around €10, while a dipole pentaband antenna for around €6 ensures wireless communication. The total cost of the sensor box is around €50. It would be possible to reduce the costs by using a cheaper microprocessor (e.g. ESP8266-based system) or through economies of scale with higher production numbers. Further expenses could include assembly, calibration, on-site installation, and mounting hardware. Operational costs such as battery replacement or recharging, maintenance, and operation of a site-wide wireless network (e.g., LoRaWAN infrastructure) must also be accounted for. Moreover, project-specific costs may arise from backend development for data collection and processing, licensing fees, and personnel training. Depending on the scale and complexity of deployment, these overheads can significantly exceed the base unit cost, and should be factored into any realistic cost-benefit analysis.

To estimate the running time of the sensor box, the energy consumption of the individual components was calculated. The following assumptions were made based on the consumption values of the installed components: The BMP180 sensor requires 5 μA per measurement, while the Arduino MKR WAN 1300 consumes between 50 and 200 μA in DeepSleep mode. During an active measurement and data transmission, the power consumption of the microcontroller increases to 120 to 130 mA. A measurement and transmission interval of one per hour was defined, with each measurement and transmission lasting around five seconds. Then the overall energy consumption can be calculated as follows:

Step 1: Calculate Hourly Consumption

$$\text{Active mode (5 sec per hour)} = 120\ mA \times \frac{5\ s}{3600\ s/h} = 0.167\ mAh$$

$$\text{DeepSleep mode (3595 sec per hour)} = 0.2\ \mu A \times \frac{3595\ s}{3600\ s/h} = 0.1997\ mAh$$

$$\text{Total Hourly Consumption} = 0.167\ mAh + 0.1997\ mAh = 0.3667\ mAh$$

Step 2: Calculate Daily Consumption

$$\text{Daily consumption} = 0.3667\ mAh/h \times 24\ h/d = 8.8\ mAh/d$$

Step 3: Estimate Battery Life

$$\text{Battery Life} = \frac{1000\ mAh}{8.8\ mAh/d} \approx 113\ \text{days}$$

The calculation shows that with a 1000 mAh Li-Ion battery, a runtime of around 113 days is possible. This confirms the suitability of the system for long-term use without frequent maintenance intervals. By optimising the operating modes, for example by reducing the measuring frequency or using energy-saving components, the battery life could be extended even further. However, in order to determine the required service life of the sensor box, it is important to analyse how long a pallet remains on a construction site and how the charging infrastructure of the sensor box is designed.

6. Conclusion and further development

The demonstrator developed shows the potential of IoT-based altimeters for material tracking on construction sites. The experiments carried out confirm that the concept works in principle, especially for multi-storey buildings where height determination is crucial for identifying the position of materials. However, the system has so far only been tested under laboratory conditions, meaning that further research into comprehensive field tests is required to validate its suitability for practical use. Firstly, it should be noted that the proposed system takes into account the specific challenges of construction logistics, such as dynamic environments and mechanical wear, by integrating into existing infrastructure. RFID and UWB-based solutions require additional infrastructure (a denser network due to their short range) and consume more energy. Mechanical wear is a problem that remains with the developed solution. However, due to its practical integration into existing means of transport (such as pallets), it is relatively well protected by the structural elements of the “host”. In order to improve the reliability of the sensors and the accuracy of the position determination, it should be investigated how the measurement times of the sensors can be synchronised. To address this issue, a real-time clock module and its regular synchronisation via the LoRa gateway could increase the measurement accuracy and reduce deviations due to time offsets. Alternatively, given this vulnerability, it is conceivable that tracking could be suspended during extreme weather events, as work is generally prohibited on the construction site during such events. In addition, improved noise suppression would be helpful to enable a more precise allocation of the sensor values to the respective floors. The concept is primarily designed for use on construction sites with multi-storey buildings. Nevertheless, intermediate floors pose a challenge as they make it difficult to clearly assign the recorded height values. The system is also only suitable to a limited extent for construction sites with several buildings or towers on the same site. Large floors or areas with many partition walls could still require manual search efforts. To overcome these limitations, a combination of several sensor technologies could be considered, for example the additional incorporation of a metric based on the signal strength. However, integrating additional sensors could increase the energy requirements and costs of the sensor boxes, which would affect their long-term economic viability. A direct transfer to other types of construction sites is not possible without further ado. For example, on linear construction sites lateral localization is needed. Barometric sensor add no value here. To reuse the LoRa equipment, an localization approach could be based on zone assignment via LoRa RSSI and gateway tiling or multilateration. This approach comes with coarse accuracy. Another approach could be the application of GNSS, which adds costs and energy demand to the sensor system. Furthermore, it is not usable indoors like in tunnels. Also, a concept for charging the batteries in the sensor boxes is still lacking. At present, the batteries would have to be changed manually, which would be impractical, especially if they were to be used extensively. One possible solution is the integration of a charging interface on the transport aids, either contact-based (charging pads/contacts) or inductive. Since the sensor-equipped transport aids typically remain on the construction site for fewer days than the maximum battery lifetime, batteries can be recharged off-site—for example at the manufacturer's facility or during pallet loading—which avoids the need for frequent on-site maintenance. In addition, opportunistic charging during handling (e.g., when pallets are placed on trucks, forklifts or staging racks equipped with charging stations) can further extend useful operational uptime without increasing device size or weight. In addition, energy consumption could be reduced by selectively switching the sensors on and off outside the construction site. For example, a handshake mechanism could be implemented at the construction site entrance to activate the sensor system only when entering the construction site and switch it off automatically when outside the construction site. The signal range tests were conducted in a medium-sized office building with six floors. While the results demonstrated sufficient coverage in this setting, they cannot be directly extrapolated to high-rise buildings with significantly more storeys, where signal attenuation is expected to be much higher due to additional structural barriers and increased vertical distance. This may result in the need for higher spreading factors implying higher airtime, lower capacity of the network, higher energy consumption and worse downlink reliability. To ensure reliable data transmission in such scenarios, a scalability analysis is necessary. This may involve the use of larger antennas, additional LoRaWAN gateways, or alternative gateway placement strategies. Consequently, a detailed and site-specific signal coverage plan is essential for high-rise construction projects to guarantee reliable operation of the smart pallet system.

Future research should therefore focus on implementing the proposed improvements and evaluating them in real construction site environments. In particular, optimising the energy supply, improving the signal quality, increasing the number of sensors used and testing under real conditions will be decisive factors for the practical suitability and economic success of the system.

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Author's contribution

Maximilian Gehring: conceptualisation, methodology, investigation, writing—original draft, writing—review & editing, visualisation. Jens Wala: writing—review & editing. Uwe Rüppel: writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare no conflict of interest.

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