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FROM IDLE TO ACTIVE: OPTIMIZING EQUIPMENT UTILIZATION THROUGH BLE-BASED INDOOR POSITIONING SYSTEM

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Abstract

The well-planned utilization of resources is the key aspect of an efficiently operated construction project. This research proposes optimizing equipment utilization through an Indoor Positioning System (IPS). Using Real-time movement data from the construction site, we developed a mechanism to track the daily usage of the equipment. The workflow consists of a Bluetooth Low Energy (BLE) beacon system that sends signals to a cloud-based database connected to a user-friendly analytical dashboard. The program then analyses the data through predefined heuristics and sends an alert message to the user's dashboard if under-utilized. This allows the user to make effective decisions to reduce idle time. This study can benefit planners by allowing them to utilize equipment at the project site efficiently.

Introduction

The construction industry is adopting novel technologies for operations and management to increase productivity and safety on construction sites. Indoor positioning systems like Radio Frequency Identification (RFID), Bluetooth Low Energy (BLE), Wi-Fi, Ultra-Wide Band (UWB) and Global Navigation Satellite System (GNSS) are some common technologies for activity monitoring at the construction area (Li et al., 2020). BLE technology has emerged as an alternative to other positioning technologies as it operates for a longer period on a coil-cell battery (Yang et al., 2020).

BLE beacons can be used to track workers and equipment on the site. Generally, BLE systems are used to detect safety conditions related to the worker's proximity (Gómez-de-Gabriel et al., 2022). However, the ability of a BLE system to detect frequent equipment movement is an opportunity to develop an automated system and improve the utilization of construction equipment.

Equipment can remain idle on the construction sites for days or even be misplaced on site. This causes a waste of resources and cost overruns for the project budgets. Moreover, the idle time of the equipment is difficult to measure without special sensors and monitoring systems which can track the equipment and monitor their efficiency (Balki et al., 2017).

This study explores the development of a data-driven workflow for monitoring equipment movement using real-time positioning data collected from a BLE beacon system. The proposed system encompasses data loading, processing, and analysis, along with a web-based user interface to visualize hoist activity and trigger alarm notifications in critical scenarios. While the framework is implemented for hoist monitoring, the methodology can be extended to any indoor construction equipment whose utilization is measurable via movement patterns. By detecting idle equipment and alerting planning teams, the system supports resource optimization and improves operational efficiency in construction projects.

Related work

Indoor positioning technologies, particularly BLE, have gained significant attention in construction management for resource tracking due to their low power consumption and good accuracy level, allowing them to have multiple applications in various fields of study (Qureshi et al., 2019, Ndebugre and Yıldırım, 2022). Baek et al. (2017) used a BLE system to track the location of a dump truck carrying ore from an underground mine. The authors used a smartphone system to visualize the navigation of the trucks and monitor their travelling time. Similarly, Ndebugre and Yıldırım (2022) developed a model of indoor localization using BLE and a machine learning algorithm. The result of their study highlights the effectiveness of object tracking using BLE, which makes it suitable to monitor the movement of construction equipment at the site (Ndebugre and Yıldırım, 2022).

BLE systems can be integrated with a cloud-based data management system to receive real-time data directly from the IoT devices. This enables direct transfer of data from IoT devices to the cloud-based system where the data is processed through pre-developed algorithms. Zhao et al. (2019) presented the use of BLE beacons in combination with Raspberry Pi devices for worker tracking within a cloud-based data collection system on construction sites. Their research highlights the importance of gathering location and time-based information on resources for effective construction management. However, the need for heuristics for accurate coverage of the location data is also highlighted (Zhao et al., 2019).

Multiple recent studies emphasize that an automated sensing system would be needed to extract real-time data from the IoT devices on-site (Kempecova and Kozlovska, 2023, Ratajczak et al., 2019, El Boudani et al., 2021). However, the system should be able to handle large-scale data sets and process them with high efficiency (Kempecova and Kozlovska, 2023).

Real-time data acquisitions provide an opportunity to utilize artificial intelligence, paving the way toward automated sensing systems for resource tracking. These systems can read and suggest patterns of movement and possible actions to be taken for improved efficiency (El Boudani et al., 2021). The findings from El Boudani et al. (2021) strengthen the concept of using real-time resource movement data to give alerts to management so that appropriate actions can be taken to reduce idle time and wasted resources. However, the first step is to acquire accurate real-time data through a cloud-based sensing system and develop a mechanism to optimize the efficiency of the resources (Zhao et al., 2019).

This study builds upon existing literature by extending the application of BLE technology beyond worker tracking and safety monitoring to visualizing equipment activity for efficient utilization. While previous studies emphasize tracking outdoor equipment to ensure safety, the current research proposes a novel approach to an alert system using automated data acquisition, analysis, and visualization methods. By utilizing the technical feasibility highlighted by earlier research, the study emphasizes on prototype dashboard, encouraging actionable outcomes from the acquired data.

In conclusion, the literature demonstrates that indoor positioning has been used to manage workers' productivity and safety. However, there are opportunities to extend this work to equipment utilization tracking. The proposed BLE-based real-time tracking system and alert system aim to enable the optimization of equipment utilization, which increases overall productivity and smooth flow at the construction site.

Method

A method for using real-time location data for equipment utilization was developed and tested in a case study. The method flowchart is shown in Figure 1. The process follows a series of systematic steps for data collection, data analysis and an alert mechanism.

The data collection system for monitoring indoor equipment movement consists of many Microcontrollers (Raspberry-Pies), placed around the construction site as gateways depending on the possible hoist movements, connected to the BLE beacons throughout a Bluetooth connection sited in a defined band range to ensure the proper connection and avoid overlapping signals connection with many gateways at the same time, a cloud-based data loading system was in charge, and user interface was employed, permit to visualize the equipment activity in determined timeline.

BLE beacons are placed in the service box of the equipment, which sends signals every second. The gateways collect signals, and the location is determined based on the strongest signal. The determined location, which refers to the gateway buffer zone, is stored in the cloud with the beacon properties information; for instance, each equipment should have a unique ID. This setup allows location-based tracking of equipment's movement in real-time. Once the data is transferred to the cloud, it is retrieved again in CSV tabular file format to feed the user dashboard. A list of algorithms is generated on the server side of the dashboard to clean, maintain the integrity, and remove redundant noise automatically. This cleaning process is performed through an automated process using a Python script, which is divided into multiple steps. The steps in the cleaning process include the removal of IPS data collected in the off time, the outliers, or false detections due to overlapping of gateway ranges through the floors and the missing values due to non-coverage areas. After the cleaning, the data is analyzed to identify the idle time of the equipment.

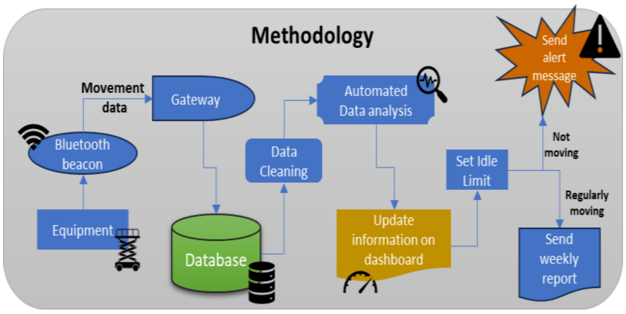

Figure 1: Automated tracking and analysis of equipment movement

The Idle time is the time frame during which the equipment has remained stationary for a certain duration. The duration is defined by the program and can be altered as per requirement. Idle time is determined by monitoring the position of the equipment on the same gateway. For instance, if the limit for idle time is defined as two working days by the user and it has remained at the same gateway, it indicates that the hoist is not in use by any worker. The information is updated on the user's dashboard, which displays real-time updates and shows the history of the movement data for each equipment separately. If the idle time is higher than the pre-defined threshold, the user gets an alert on the dashboard. The user may observe and take necessary action to optimize the equipment utilization. The data is also compiled for each week and stored as history so that historical trends can be analyzed. The following section will present the implementation of this method in a case study.

Case Study for Hoist Movement

A multi-story construction site with multiple functions (sports, events, retail) was chosen to validate the proposed method. The building had eight floors, and each floor had a few hoists for the trade workers to perform installations at ceiling height. The management was interested in hoist utilization because they saw low usage of the hoists.

A gateway placement was planned on all the floors so that the gateways would cover most of the area where the hoist movement was possible. BLE beacons were placed inside the hoists to collect and receive real-time data in the cloud-based system. The used indoor positioning system was Icons, which has been previously used to track worker productivity (Zhao et al., 2019). Figure 2 shows the Raspberry Pi Gateway along with a Wi-Fi dongle (for internet connectivity) on the left side. On the right-hand side, it shows the coin-sized BLE beacon, which was placed inside the hoists to capture the signals due to their movement. Each gateway was labelled with a specific code to identify the gateway's location in the ICons system.

Gateway with Wi-Fi Dongle

BLE-Beacon placed inside equipment

Figure 2: Hardware system used for Equipment tracking

Data collection and processing

Five hoists were selected for the data collection, and the BLE beacon on each hoist had a unique ID number (H155, H160, H165, H168 and H169) along with the floor number associated with the hoist. This information made it easier to locate the hoist data in the database where the IPS data could be collected using the Icons system.

The gateways were continuously catching signals as they were connected to a direct electric supply source, so we had overnight detections for the Hoists. The beacons, placed in the hoists, never left the site, and they were continuously sending signals. However, the system should only process the data from working hours and workdays. After observing the workers' IPS data, we determined the active working time on site to be from 7 am to 6 pm, matching the workers' work time. Similarly, the weekend days were also deducted from the IPS data for the hoists. Defining working time for the hoists was important to calculate meaningful utilization metrics. This time range could be adjusted in the dashboard system as per the site conditions. This process was conducted as part of data cleaning.

Because there were not enough gateways to achieve full detection coverage of each floor, there was some missing data for the hoists. To fill these gaps, we applied Zhao's (2019) heuristics to calculate the missing data, i.e. dividing the undetected time equally between the gateway detected before the loss of signal and after the next detection. The total duration in the gateway area was calculated from the first detection at the gateway to the last detection at the gateway. Then, the process continued for the next gateway. After cleaning and structuring the data, various analyses were performed using the data set, i.e. idle time calculations, heat maps for presence in various locations and daily frequency of movement. The data analysis process was also developed through an automated Python script that took cleaned data as input and provided results as visualizations.

Data Analysis and Visualization

After cleaning the data and preparing new data items for analysis, we developed a data pipeline integrated with an analytical dashboard to visualize the results.

First, we connected the processed files to a dedicated data warehouse containing only the cleaned data. Since the beacons transmit signals every second, the dataset grows exponentially with the number of hoists. Each hoist generates thousands of weekly entries with over 10 column attributes. This volume poses a challenge for real-time monitoring. To address this, we optimized the data structure by transitioning from a raw tabular format to a column-based database architecture. Each attribute is stored separately in this model, allowing the system to retrieve only the required columns during queries rather than loading the entire dataset. We implemented this using Duck DB (Raasveldt and Mühleisen, 2019, Kohn et al., 2022), a high-performance analytical database that supports efficient columnar operations.

All data processing algorithms occur on the server side of the dashboard. For the front-end interface, we designed interactive UI components, including:

- **Line charts** and **heatmaps** to visualize hoist activity trends.
- An **alert box** to display critical notifications.

Users can filter data by Hoist ID and select either the most recent week or a custom historical time range. Based on the query parameters, the dashboard dynamically updates to reflect the hoist activity.

Results

The analytical results were compiled. Figure 3 shows a comparison between the total time spent on the site by the hoist and the total time it remained at a single place without movement. The percentage of inactive time to total time was also calculated, which is shown with a dotted line in the graph. The H168 hoist was the most active hoist, with only 18% inactive time. The H160 hoist remained continuously inactive for a few weeks, hence, it has the highest idle time of 72%.

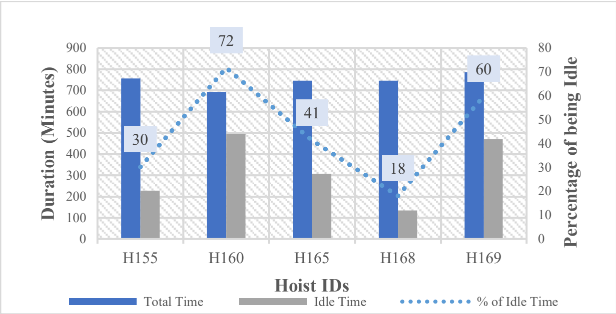

Figure 3: Duration vs Percentage of Idle Time

A heat map of H168 is shown in Figure 4. The figure indicates the time spent by the hoist on each gateway of the floor. The hoist remained on the same floor during the whole period of data collection. The heatmap shows that the hoist was frequently used. However, it remained idle for a noticeably short period, around mid-May. The overall view of the figure is self-explanatory to the user, and it can be immediately perceived whether the hoist is in continuous use or idle.

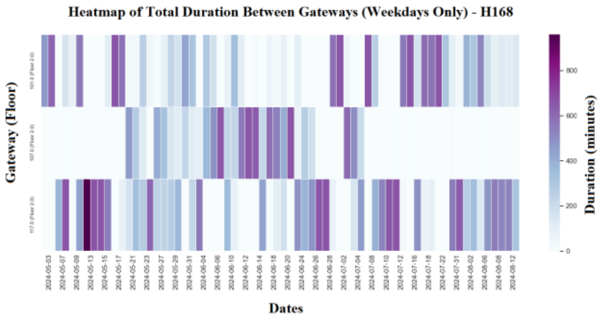

Figure 4: Heatmap of H168

Similarly, a line plot of H160 in Figure 5 shows the movement frequency of the hoist between the gateways each day. The hoist remained idle for the first two months (no movement shown). After the idle period, there is a period of activity during the next two months. However, even in this period, the hoist also remained under-utilized for a few consecutive days.

As a part of the alert mechanism, a dashboard system, shown in Figure 6, was designed to show these statistics in a user-friendly interface. The dashboard consists of line plots and heat maps of the equipment, with an option to switch modes to observe overall scenarios of all the equipment in use. The attributes of this system also include automated data collection, analysis, and display results on the screen. Moreover, it will also send alert messages to the user along with the equipment ID if the equipment has remained inactive for a certain period, which is pre-defined by the user. New equipment can also be added to the dashboard system.

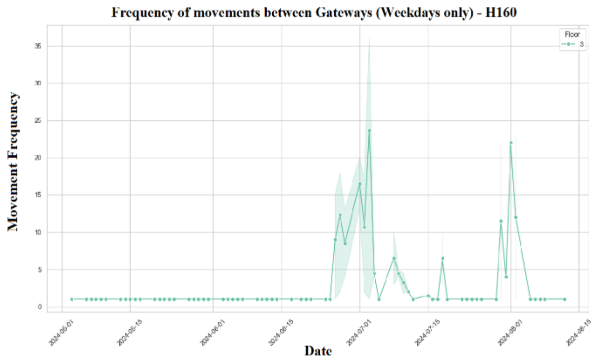

Figure 5: Line Plot for Hoist 160

Discussion

Indoor positioning has been used for the productivity of workers and safety purposes (Zhao et al., 2019; Kempe Cova and Kozlovski, 2023). However, the utilization of equipment has not been extensively researched. The case study demonstrated that hoists were unutilized. This was assumed by the management, but the system was able to provide data on utilization. The results from the study indicate zero movement of the hoist can be interpreted as under-utilization of the hoists. This analysis can help raise alarms for the user to efficiently utilize the equipment and reduce resource wastage.

The same system can be applied to any equipment in indoor construction if a beacon can be attached to it without impeding use, e.g., vacuum cleaners, ladders, dryers, concrete pumps, etc. If the inactiveness of the hoists is communicated to the planning team on time, there is a possibility of improved utilization or moving the inactive resource to another construction site where it is required. This type of research related to resource utilization can help the site staff manage the resources more efficiently and usefully.

The proposed method is not only limited to movement detection, but it also has potential for wider applications in construction sites. This method can be integrated with preventive maintenance. The frequency of movement, idle times and other related analysis can provide an insight into the current working condition of the equipment. The usage pattern and movement frequencies can indicate the need for scheduled maintenance. For example, more frequently used equipment would need shorter gaps between scheduled maintenance, while less-used equipment would have a longer maintenance time. Moreover, the inactiveness of equipment could also be due to technical defects which are not reported by the workers to the supervisors. If the equipment is highlighted on the dashboard due to inactivity, maintenance staff will

Figure 6: Dashboard User Interface

automatically notice it. This proactive approach can enhance the life of the equipment and reduce maintenance costs.

Tracking the equipment through an advanced IPS system and developing an interactive user interface for efficient utility is an innovative approach for technology employment. These tools are especially useful for non-technical users as they present complex movement data in a user-friendly manner, which is difficult to assess manually. Visualization like this graphical interface can facilitate in-time decision making and support effective resource management.

However, the Icons system has certain limitations. For instance, it experiences repetitive false detections due to signal overlap between floors. A hoist on the second floor, for example, may be detected by a gateway in the same buffer zone on the adjacent floor or even by a gateway two floors above. This creates ambiguity in cleaning operations due to the predefined algorithmic heuristics.

Additionally, while adjusting the Bluetooth range of the gateways could partially address this issue, it is not a comprehensive solution, as it would require deploying numerous microcontrollers to ensure full coverage across the entire construction site.

Furthermore, the patterns of movement studied from the real-time data can be a valuable resource to link the system to the machine learning algorithm. Recently, Maaloul et al. (2023) explored the integration of machine algorithms into the BLE-based indoor positioning system to improve the accuracy of the IPS system. The results indicate that a machine learning algorithm can improve the data analysis process and optimize the pattern recognition process of the movement of the equipment.

Although the study mentions the use of BLE beacons for equipment tracking, however, there is potential to explore alternative options for the positioning of indoor equipment. There are modern construction machineries that come with built-in sensors and monitoring devices that can acquire similar data without the need for external devices. Alternatively, the retrofitting of existing machinery with the BLE beacons provides a suitable solution to upgrade the existing practice of equipment tracking. Retrofitting is a cost-effective option instead of replacing the existing equipment with modern equipment, especially if they are fully functional.

To summarize, there are numerous opportunities to enhance the alert system for efficient utilization of resources through integration of advanced technologies, i.e. machine learning algorithms, to transform the resource management practices on construction sites. Being a cost-effective solution, BLE beacons can be used for multiple tracking streams. Using the cloud-based system for tracking all resources, there is an advantage of adding more beacons at any time to the system to track new resources. This research contributes by demonstrating a method for effectively utilizing indoor positioning data of indoor equipment to extract meaningful information regarding its movement. These insights can be utilized to monitor and control the efficient use of equipment, eventually reducing resource waste.

Conclusion

In this research, an IPS-based system was developed to evaluate equipment utilization in indoor construction in real time. It was implemented in a case project where it was observed that the utilization rate of hoists was variable and, for some hoists, extremely low. There is a significant opportunity to improve the productivity of equipment usage with real-time data. This approach is well-suited for the indoor equipment that does not have complex IT systems and whose usage can be measured through movement data.

In future research, this work can be extended by incorporating a user feedback option in the prototype dashboard. This feedback can then be integrated with AI and ML algorithms to develop the predictive abilities of the system and optimize actions for improved resource utilization. Moreover, there is an opportunity to enhance the content of the dashboard system and integrate it with workers' movement and productivity management. By broadening the application of IPS systems using BLE beacons, organizations can achieve a holistic view of resource positioning and tracking, eventually increasing the efficiency of resource planning and management in construction projects.

Acknowledgment

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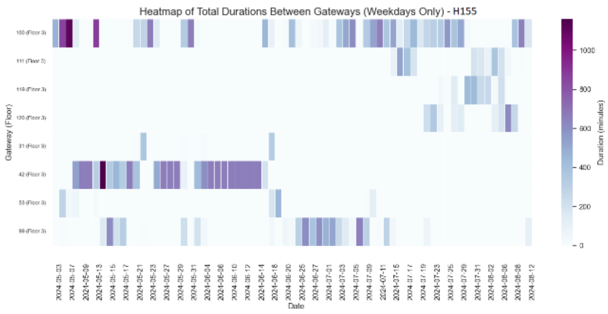
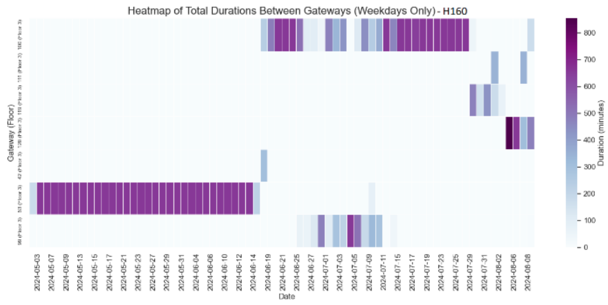
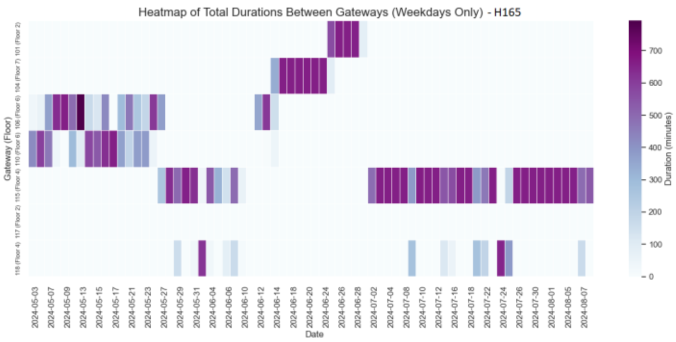
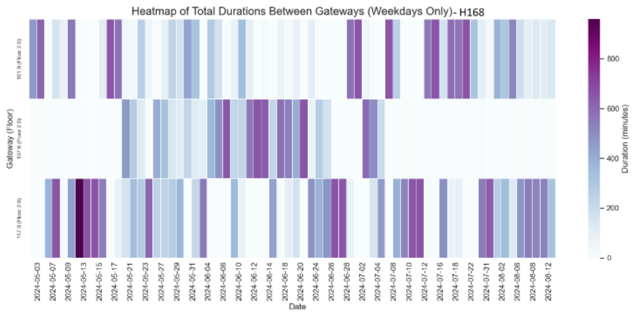
Appendix

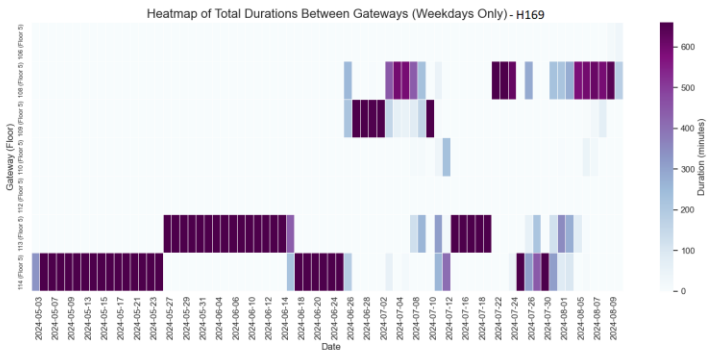
Heatmaps



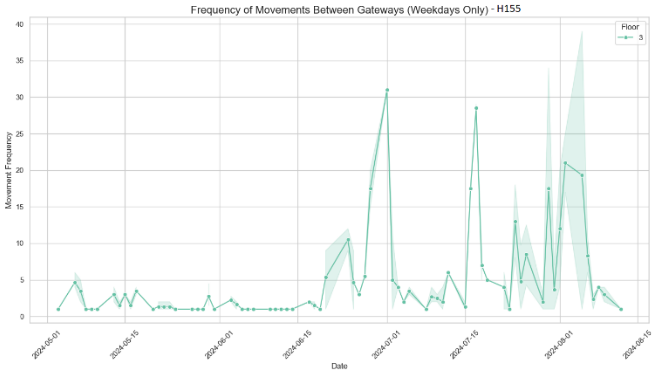




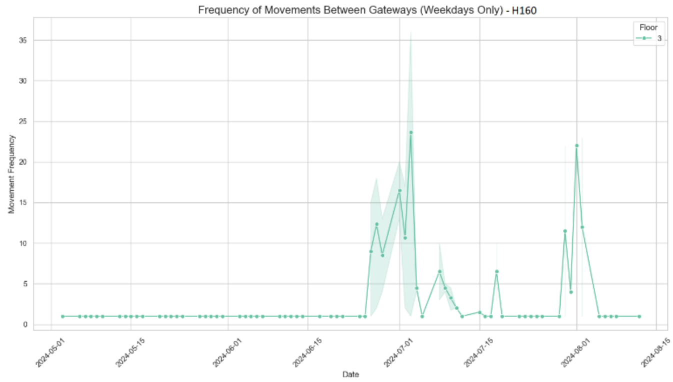




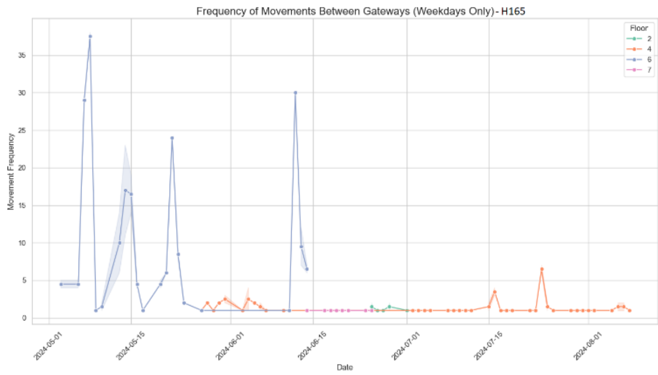
Line Plots



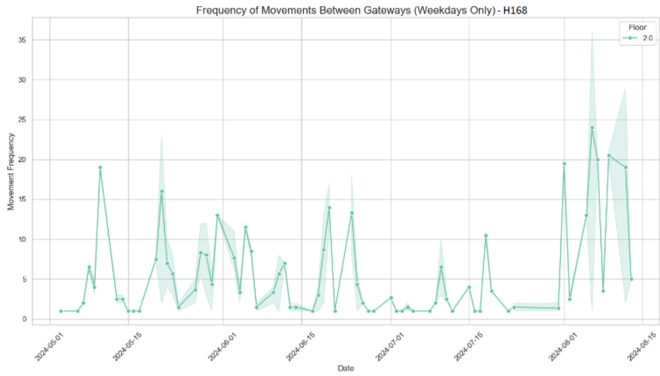
Frequency of Movements Between Gateways (Weekdays Only) - H155
Movement Frequency
Date
Floor
3



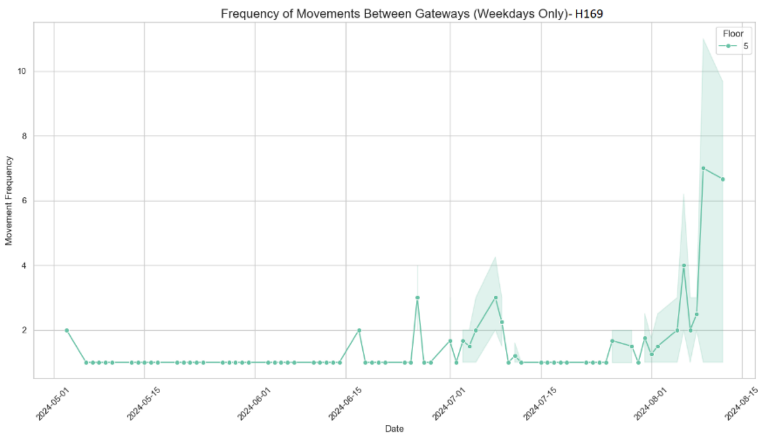
Frequency of Movements Between Gateways (Weekdays Only) - H160
Movement Frequency
Date
Floor
3



Frequency of Movements Between Gateways (Weekdays Only) - H165
Movement Frequency
Date
Floor
2
4
6
7



Frequency of Movements Between Gateways (Weekdays Only) - H168
Movement Frequency
Date
Floor
2.0



Frequency of Movements Between Gateways (Weekdays Only)- H169
Movement Frequency
Date
Floor
5