# Digital Twin Construction in Practice: A Case Study of Closed-Loop Production Control Integrating BIM, GIS, and IoT Sensors

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**Abstract:** Digital twin construction (DTC) integrates digital representation of product design and process planning, automated monitoring on site, intelligent data interpretation, and predictive analytics to provide managers with situational awareness and guide subsequent cycles of production planning and control. This study presents a case study of a DTC system integrating building information modeling (BIM), the Internet of Things (IoT), and GIS for real-time monitoring and process optimization in an industrial silo construction project in Canada. The system consists of four key components: IoT sensors that collect real-time construction data, automated data transmission and storage, BIM-based design and planning models, and interactive dashboards for project monitoring and decision-making. The system enabled just-in-time pull delivery of steel elements, precise placement of components within the slip-formwork, and continuous progress tracking. As a result, construction time was reduced by 28% and material wastage decreased by 15% due to data-driven decision-making and real-time monitoring. The primary contribution of this study is demonstrating a structured approach to integrating DTC technologies into construction workflows, providing a practical framework for bridging digital models with real-time execution. This research highlights how the integration of BIM, IoT, and GIS enhances construction accuracy, efficiency, and automation, addressing challenges related to interoperability, real-time monitoring, and predictive analytics. Despite challenges such as the initial setup costs and specialized staff training requirements, the long-term benefits, including improved resource allocation, cost savings, and enhanced project management capabilities, justify the investment. The findings suggest that adapting advanced DTC systems can significantly enhance construction productivity, accuracy, and sustainability, leading to better-managed and more efficient projects. Future research should explore scalability across different construction sectors and locations to further validate the economic and operational impact of this approach. **DOI: 10.1061/JCEMD4.COENG-16588.** 

**Author keywords:** Building information modeling (BIM); GIS; Internet of Things (IoT); Data visualization; Data integration; Construction progress tracking.

## Introduction

Effective management of the construction process is crucial for delivering projects on time, safely, profitably, and with the requisite quality of work. A broad thrust of research in the automation of construction indicates that integrating various digital technologies, such as artificial intelligence (AI), cloud computing, building information modeling (BIM), data analytics, the Internet of Things (IoT), photogrammetry and/or laser-scanning surveys, and GIS, might enable design of construction production systems that empower construction teams to achieve these objectives effectively (Chen et al. 2018; Kochovski and Stankovski 2018; Yarmohammadi and Castro-Lacouture 2018; Zhang et al. 2018; Wu et al. 2019; Boje et al. 2020; Ozturk 2021). However, most of these efforts have focused on implementation of isolated technologies, achieving limited results (Hasan and Sacks 2023). Instead, an integrated, holistic approach is needed (Anil et al. 2023).

Boje et al. (2020) suggested that the concept of digital twins may be a useful paradigm for broad system integration, and Sacks et al. (2020) defined a holistic approach called digital twin construction (DTC). DTC integrates digital representation of product design and process planning, automated monitoring on site, intelligent interpretation of the data, and predictive analytics to provide situational awareness for managers and to guide subsequent cycles of production planning and control. Product design and process information (intent information) are prepared and provided using BIM processes and technologies (Sacks et al. 2025). Monitoring of production and products on site is performed using photogrammetry or laser scanning, radio frequency identification (RFID) tagging, bluetooth low energy (BLE), and a variety of sensors communicating as IoT devices (Valinejadshoubi et al. 2021a, b). The data collected from these tools are merged and interpreted to provide project status information, which can be conveniently compiled and stored in graph databases in the cloud (Schlenger et al. 2025). Comparing intent against status information provides construction managers with detailed situational awareness and enables

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them to make well-informed decisions regarding possible adjustments to the production system. The cycle of planning, doing, checking, and acting (PDCA) (Deming 2000) is repeated throughout the construction process.

The primary goal of this research was to develop and validate a prototypical DTC system capable of real-time monitoring, data integration, and decision support for concrete construction projects. By leveraging BIM, IoT, and GIS technologies, the system enables continuous comparison of construction progress with BIM models and provides real-time insights to construction managers through interactive dashboards. Beyond demonstrating the feasibility of this specific implementation, the research aims to advance DTC methodologies by illustrating the practical application of a fully integrated system that follows the PDCA cycle of production planning and control.

To achieve this, the study establishes the following key objectives:

1. Develop a fully automated DTC system that integrates BIM models, IoT sensors, and GIS technology to enable real-time monitoring of concrete construction operations through cloud-based platforms.
2. Enhance data interoperability and automation by implementing structured workflows using feature manipulation engine (FME) software to facilitate seamless data transfer and processing between file transfer protocol (FTP) servers and structured query language (SQL) databases, ensuring efficient integration of BIM, IoT, and GIS.
3. Demonstrate the system's ability to improve precision in structural elements placement, specifically focusing on steel plate and opening positioning in slip-formed concrete construction. This objective serves as a practical validation of the DTC system's accuracy and adaptability, showcasing its potential application in other continuous concrete pouring and slip-forming projects.
4. Develop and implement specialized dashboard interfaces that serve as a generalizable visualization and monitoring toolset for DTC applications. These dashboards facilitate
   - tracking concrete pouring progress in terms of height and volume, ensuring compliance with design parameters;
   - providing real-time updates on critical construction parameters, such as elevation, temperature, rotation, pitch, and roll, enabling automated alerts and proactive decision-making; and
   - displaying historical data trends of IoT sensors to analyze long-term construction performance and deviations.
5. Validate the system's effectiveness through real-world implementation, assessing its ability to improve project management practices, data interoperability, and workflow automation while addressing key barriers such as setup costs and specialized staff training requirements.
6. Assess the DTC system's broader impact on project efficiency, including reductions in construction duration, material waste, and improved productivity, thereby providing quantifiable evidence of the benefits of integrating DTC methodologies into construction workflows.

The remainder of the paper is organized as follows. The next section presents and reviews the literature on the subjects of BIM, IoT, and GIS integration. Section "Hardware and Software Implementation" describes the hardware and software implementation.

## Literature Review

BIM has revolutionized the architecture, engineering, and construction (AEC) industry, facilitating collaboration and enhancing project outcomes. Its applications have grown to support a variety of engineering processes, such as seismic risk assessment (Valinejadshoubi et al. 2018a), structural health monitoring (SHM) (Valinejadshoubi et al. 2016, 2018b, 2019), operational monitoring (Valinejadshoubi et al. 2021a, b), and automated data integration and visualization (Valinejadshoubi et al. 2024a, b). These advances have made BIM the information backbone of modern construction projects, and its integration with emerging technologies like the IoT and GIS (Dave et al. 2016) has opened new possibilities for improving project management, design, and construction.

Numerous studies have highlighted the potential of IoT-BIM integration to enhance construction processes (Tang et al. 2019; Moradi et al. 2019; Oyekan et al. 2021). IoT-enabled BIM systems allow real-time data collection from sensors and devices, improving project tracking and informing decision-making. For example, Tang et al. (2019) reviewed these synergies, underlining emerging trends including IoT devices for on-site monitoring, automated construction workflows, and predictive analytics. However, construction companies adopting these technologies face challenges and issues in integrating BIM and IoT within information and communication technology (ICT) implementation (Gao and Pishdad-Bozorgi 2019); Regona et al. 2022; Wong et al. 2018), particularly interoperability, as Altohami et al. (2021) pointed out.

Data exchange issues between BIM platforms and IoT devices remain a significant hurdle, making seamless integration difficult. Lee et al. (2015) addressed this issue by developing a prototype that uses drones and sensors to monitor construction progress, but their approach lacked scalability for large-scale projects. Shen (2022) proposed a method that combines BIM and IoT technologies to generate three-dimensional (3D) model files, engineering quantity files, and construction schedule plans. Their approach utilizes BIM and IoT technologies for effective material management in construction projects. Sarkar et al. (2023) developed an integrated BIM-IoT prototype designed to automate the monitoring of mega-complex infrastructure projects. Their prototype facilitates data management for construction projects via a decentralized common data environment (DCDE). Lokshina et al. (2019) proposed a system design that utilizes blockchain technology in the framework that involves integrated BIM and IoT technologies.

Although BIM platforms and IoT devices have each reached advanced levels of development, there is still a need to create effective integrated systems that address practical problems (Fialho et al. 2020). Moreover, integrating IoT with BIM and GIS continues to face significant challenges, especially in merging parametric and geospatial databases. The interoperability challenges remain significant despite the development of frameworks to overcome these obstacles, such as the one proposed by Bansal (2021), which suggests a multidisciplinary approach to building life-cycle management (BLM).

In parallel, integrating GIS with BIM has gained attention for its ability to provide spatial context to construction data, thereby improving project planning and asset management (Santacruz 2022). GIS allows for more precise geographical and topographical insights during construction. Han et al. (2020) and Kang and Hong (2015) explored the role of GIS-BIM integration in managing construction schedules, material logistics, and on-site safety, demonstrating its potential to enhance project efficiency. However, the complexity of integrating spatial (GIS) and parametric (BIM) data presents challenges (Wan Abdul Basir et al. 2018), primarily because of incompatible data formats and differing coordinate systems, as highlighted by Wang and Xie (2022).

Recent advancements have seen the emergence of the DTC concept (Sacks et al. 2020), which aims to leverage the information provided by BIM, IoT, and GIS technologies into a comprehensive digital model that represents real-time project conditions. Teizer et al. (2022) introduced a digital twin for construction safety (DTCS), which integrates real-time sensor data with BIM to monitor hazards and risks on construction sites. Shariatfar et al. (2022) extended this by integrating four-dimensional (4D) BIM models, cloud computing, and real-time data to support decision-making and safety management in dynamic construction environments. Liu et al. (2023) explored how a DTC system can enhance urban excavation safety through multisensory systems, and Yan et al. (2021) presented a DTC framework for life-cycle asset management, integrating BIM data to monitor space, energy, and maintenance operations. Additionally, Jahagirdar and Leicht (2023) explored the potential of digital twins in automating construction processes and enhancing project control through real-time data integration.

Despite the growing interest in DTC, much of the research remains theoretical or limited to specific applications, restricting its full potential. Challenges in practical implementation, such as synchronizing large data sets from BIM, IoT, and GIS platforms, a lack of standardized protocols for integrating DTC systems, and concerns over data privacy and security in cloud-based platforms, constrain widespread adoption. These challenges were also noted by Abugu et al. (2024), who examined the costs and benefits of implementing DTC systems in construction, highlighting that high implementation costs and technical limitations prevent their broader use. Jacobellis and Ilbeigi (2022) discussed the data availability issues in creating digital twin cities, emphasizing that comprehensive, integrated data collection systems are required to ensure the effective application of digital twin technologies in smart urban management.

The literature revealed that this integrated approach has received limited attention in construction projects, despite the potentially significant benefits of creating a comprehensive DTC model that includes spatial, design, and construction parameter information. Therefore, this study aimed to implement, test, and demonstrate a novel DTC solution that utilizes BIM, IoT, and GIS technologies, offering real-time monitoring of construction activity. This required overcoming the limitations seen in previous research, such as the challenge of data interoperability and synchronization, and providing a solution for real-world applications.

## Case Study Project

This case study reports on the innovative construction techniques implemented at Ciment Québec in Canada for building six 45-m-high concrete silos, which are utilized across various sectors, including agriculture, manufacturing, and storage. The silos required 3,173 $m^3$ of concrete for a stable and durable foundation, along with 15,500 $m^2$ of formwork to achieve precise structural shaping and detailing. A total of 511 steel plates were incorporated to reinforce the silos, ensuring resilience against internal pressures from stored materials. Additionally, 200 t of reinforcement steel were used to provide the necessary tensile strength and stability for the silos, supporting the weight of the concrete and enhancing resistance to lateral forces. The construction employed slip forming, chosen for its ability to produce continuous, seamless concrete structures that are essential for maintaining the integrity and functionality of the silos. The concrete was poured simultaneously in all six silos over a continuous 9-day period. The seamless nature of the slip-formed concrete free from joints provides enhanced performance characteristics compared with traditional segmented construction, significantly improving the durability and strength of the structures.

The project involved careful monitoring of several key parameters to ensure the integrity of the slip-forming process. A significant challenge was the accurate positioning of steel plates and openings, crucial for maintaining structural integrity and functionality. The continuous nature of the pour required precise coordination and proactive problem-solving to adjust the formwork as the structure ascended.

The construction required the coordinated efforts of 120 workers, including supervisors and managers, operating in 12-h shifts. This intense work schedule necessitated high-volume, reliable communication and adequate information transfer from one shift to another, ensuring that all team members were consistently updated and informed. Materials, components, and labor were pulled to the necessary silos according to progress in curing concrete sections as monitored by the DTC system, using information visualized in the data interface. This was vital for maintaining the quality and safety standards for successful project completion.

The use of slip forming not only ensured the rapid construction of high-quality, durable silos but also demonstrated the potential for scaling this technique in similar industrial projects. The successful completion of the silos with high structural integrity and functionality underlines the value of continuous, joint-free construction in critical infrastructure. The Ciment Québec project serves as a benchmark in the construction of concrete silos using slip-forming technology. It showcases how advanced construction techniques, combined with careful monitoring and workforce coordination, can result in structures that meet high safety and quality standards. This case study provides valuable insights for future projects that aim to optimize construction efficiency and structural performance in industrial applications.

## System Architecture

The system architecture was designed to implement a standard DTC process based on a PDCA framework (Sacks et al. 2020), with the following activities and components:

1. Plan: Design and plan the product and the process and compile the information in a BIM model. This expresses the design and planning intent of the construction project.
2. Do: Construction planning and control that leads to construction on site according to the design and plan.
3. Check: A monitoring and information interpretation system that measures conditions on site and compiles the project status model, including comparison of the status with the intent and visualization.
4. Act: Provision of recommendations for revising designs or plans, and of production pull signals for the next phase of construction. Fig. 1 outlines these principal components of the DTC system.

The developed DTC system integrates BIM, IoT, and GIS technologies, enabling real-time automation of data acquisition, processing, and visualization. The BIM model, developed in Autodesk Revit version 2023, contains silo structural geometry, reinforcement details, and formwork components, which were stored in Autodesk Construction Cloud (ACC) for collaborative access. The project intent information (PII), extracted from the BIM model, serves as the reference for monitoring construction progress. Fig. 2 shows a perspective view of the BIM model of the silos and a neighboring machine building, superimposed onto an aerial photo taken by a drone.

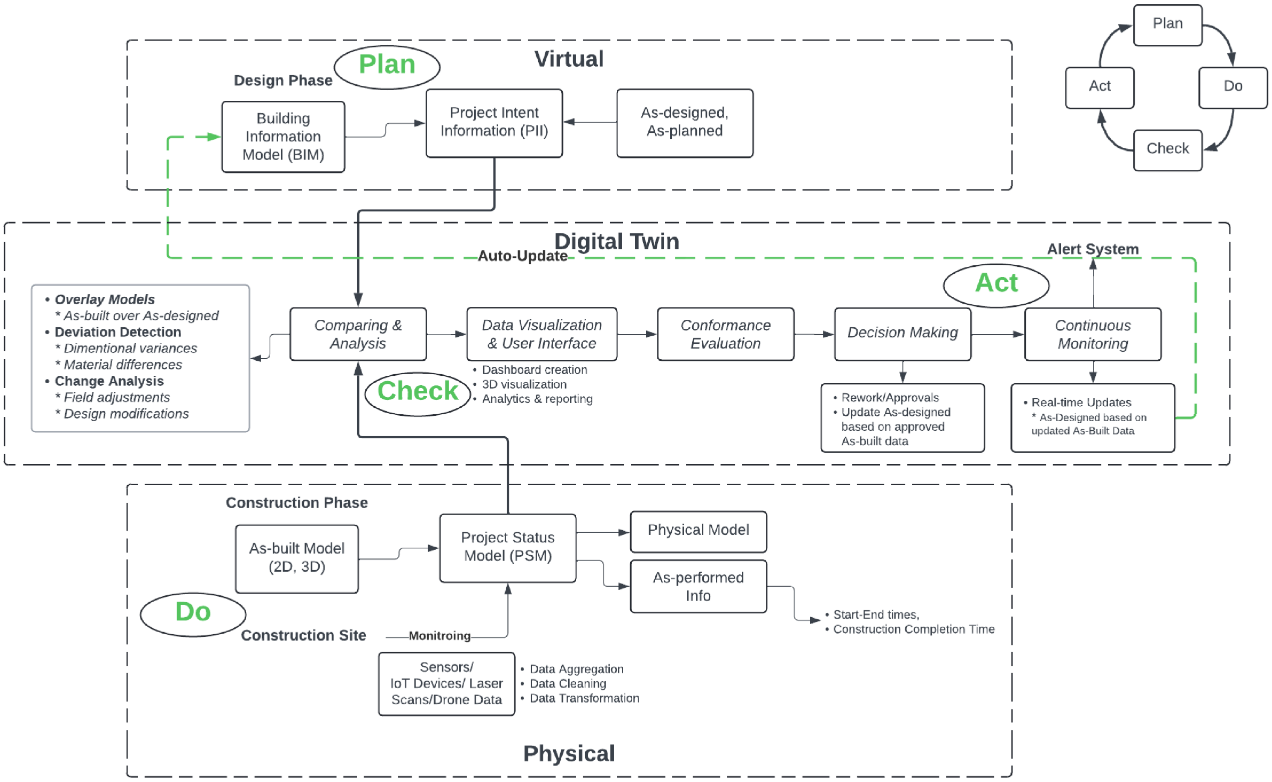


**Fig. 1.** DTC system architecture that guided the implementation of the system.

**Fig. 2.** Concrete silo structural BIM model view superimposed on a drone aerial photo. (Images by authors.)

The project status model (PSM) plays a central role in bridging digital planning with physical execution by integrating real-time monitoring data with the intent model from BIM, ensuring continuous alignment between design and construction progress. The PSM processes sensor data collected on site, including elevation, pitch, roll, rotation, and temperature, and compares it with the planned parameters in the BIM model. This real-time analysis dynamically generates key project metrics, such as the height of poured concrete, total volume of material placed, and alignment verification, ensuring quality and precision during the slip-forming process. These insights are crucial for decision-making, minimizing construction deviations, and preventing structural inconsistencies.

The monitoring function comprises a data-acquisition (DAQ) component and a data-transfer component, designed to collect, process, and transmit real-time construction data. The DAQ sensors, installed on site, continuously measure five critical construction parameters, namely, elevation, pitching, rolling, rotation, and temperature, to ensure precise control over concrete pouring and structural alignment. The elevation parameter was monitored to track the progress of construction concrete pouring and ensure the accurate height of the concrete silos. The pitching parameter was measured to verify that the silos were perfectly vertical, enhancing structural integrity and ensuring proper load distribution.

The rolling parameter was tracked to prevent rotational deviations during construction, ensuring the silos did not twist around their vertical axis. Rolling can impose stresses on parts of the silo not designed to withstand them, potentially leading to cracks, and weakening of the concrete structure, thereby reducing the silo's overall life span and effectiveness. Significant rolling could also present operational challenges, such as difficulties in material discharge. Moreover, rolling can cause uneven distribution of the internal load from stored material, which might intensify the rolling or lead to other structural issues like buckling or further twisting.

The rotation parameter was measured to prevent post-construction problems such as uneven load distribution, structural degradation, and misalignment of the silos' discharge mechanisms. Finally, temperature values were monitored to oversee the concrete curing process, which is critical for achieving optimal strength and durability of the silos. The data-transfer module automates the data flow between components using FME software, facilitating real-time data retrieval from a FTP server, processing it, and transferring it to the data storage module for analysis.

The data storage module, built on Microsoft Azure SQL Databases version 12, manages project status data by maintaining two automatically updated tables: the Live Data table, storing instantaneous sensor readings, and the Time History Data table, which archives historical construction data for trend analysis. The outputs from the PSM are directly used for visualization through custom dashboards (Figs. 7 and 8), displaying real-time progress percentages, concrete pouring rates, and structural integrity metrics, which are computed by integrating BIM geometric properties with sensor data.

Lastly, the data visualization module integrates both status and intent information, allowing for the overlaying of real-time monitoring data onto the BIM-based design intent. It presents users with a visual representation of the actual state of construction on site, ensuring real-time synchronization between planned and actual progress. The system employs ArcGIS Server-based dashboards, designed to visualize spatial data, BIM data, and IoT sensor data simultaneously. GIS plays a critical role in this integration by mapping real-time construction parameters, such as elevation, pitch, roll, rotation, and temperature, onto georeferenced site maps. The ArcGIS platform enables project managers to monitor each silo's construction progress within its spatial context, ensuring accurate tracking and compliance verification.

Additionally, GIS facilitates the integration of SQL database outputs with BIM models, providing a comprehensive, real-time visualization of project status and ensuring alignment between on-site conditions and the planned design. This seamless integration enhances decision-making efficiency, enabling project managers to analyze construction parameters, monitor compliance with quality thresholds, and take immediate remedial actions when deviations are detected.

By leveraging BIM, IoT, and GIS in a unified framework, this system enhances construction accuracy, efficiency, and decision-making, offering a scalable solution for real-time project monitoring and optimization.

## Hardware and Software Implementation

The principal DTC system architecture was implemented using numerous hardware and software components. Fig. 3 shows the full set of components and the flow of information from one to another. The figure and the text below start with the monitoring equipment, continue with the data-transfer hardware and software, then describe the intent and status information storage components, and finally, the data visualization software.

The implemented system directly maps to the theoretical framework described in Section 4 (Fig. 1), which follows the PDCA cycle. In the Plan phase, the BIM, developed in Autodesk Revit and stored in ACC platform, serves as the PII. This model represents the planned construction elements, including the silo structural geometry, reinforcement details, and formwork components, ensuring consistency between design intent and field execution.

The Do phase involves real-time data collection through DAQ systems, which were attached to the underside of the top formworks at selected locations before concrete pouring. These systems collected data on critical construction parameters using wireless sensors embedded in the LaserTilit90 sensory modules (Worldsensning, Barcelona, Spain). The system's gateway, positioned 50 m from the sensors, received and transmitted data to the FTP cloud server using an IP address and a port number via the Internet (Data transfer 1), with a SIM card providing network connectivity.

The Check phase is facilitated by automated data processing and storage. The sensor data, stored in the FTP cloud server, were retrieved (Data transfer 2), transformed, and processed using a workflow developed in the FME platform. Using this workflow, the sensor data were transmitted to a Microsoft Azure SQL database, where they were stored in the Live Data table. The table contained real-time sensor readings, including ObjectID, Silo_Name, Date_and_time, and elevation, pitching, rotation, rolling, and temperature values, and was updated every minute. Before each update, the data were transferred to the Time History Data table to maintain a complete historical record, enabling trend analysis and quality assessment.

Also in the Check phase, the system integrates real-time monitoring data with the BIM model for visualization. The Time History and Live Data tables' data were transferred to the ArcGIS platform, which contained both GIS data and the BIM model. Additionally, the BIM models in Autodesk Revit and computer-aided design (CAD) formats were uploaded to the ACC platform, automatically linking to the SQL database for seamless visualization.

Four visualization dashboards were developed within the ArcGIS platform to monitor both sensor data and the progress of concrete pouring. The sensor data visualization dashboard was dynamically updated from the SQL database table, and the concrete pouring progress visualization dashboard was updated daily by the construction team using a specific BIM parameter called Status. To enhance clarity, a color-coding scheme was applied to display the construction status of various concrete structural elements.

Finally, in the Act phase managers make decisions concerning rework approvals, updates to the design, and changes to resource assignments. These are delivered to the Plan phase, and the cycle repeats.

The structured mapping of the theoretical framework (Fig. 1) to the actual implementation (Fig. 3) ensures a systematic integration of BIM, IoT, and GIS for real-time monitoring and decision-making. The seamless flow from design intent (Plan) to real-time execution (Do), automated validation (Check), and adaptive decision-making (Act) strengthens the practical applicability of the developed system, enabling construction teams to track progress, ensure compliance, and make timely adjustments.

### *Hardware Configuration of the System*

The DAQ system used in this study included several hardware subcomponents:

- LaserTilt90 module: Each module included a laser distance meter to measure the relative distance to a reference point that were either natural surfaces or target foils. Additionally, a tiltmeter was integrated to measure changes from the vertical level, either on the ground or in structures, ensuring precise monitoring of the formwork's position. The LaserTilt90 was responsible for collecting elevation, pitch, roll, and rotation data.
- Thermocouple sensor: Because the LaserTilt90 does not measure temperature, an additional thermocouple was deployed to monitor ambient and concrete temperature. This was crucial for ensuring optimal concrete curing conditions
- Gateway: The LaserTilt90 modules transmitted data via long-range radio to a gateway, which was connected to the Internet. The maximum transmission range of the gateway was up to 15 km (9 mi).
- Battery: The LaserTilt90 is a battery-powered autonomous device. It is IP68 certified, ensuring dust and water resistance, and functions in an operating temperature range of 0°C to +50°C.
- SIM card: A SIM card was installed in the gateway to establish a high-speed internet connection, enabling seamless real-time data transfer from the site to the cloud server.



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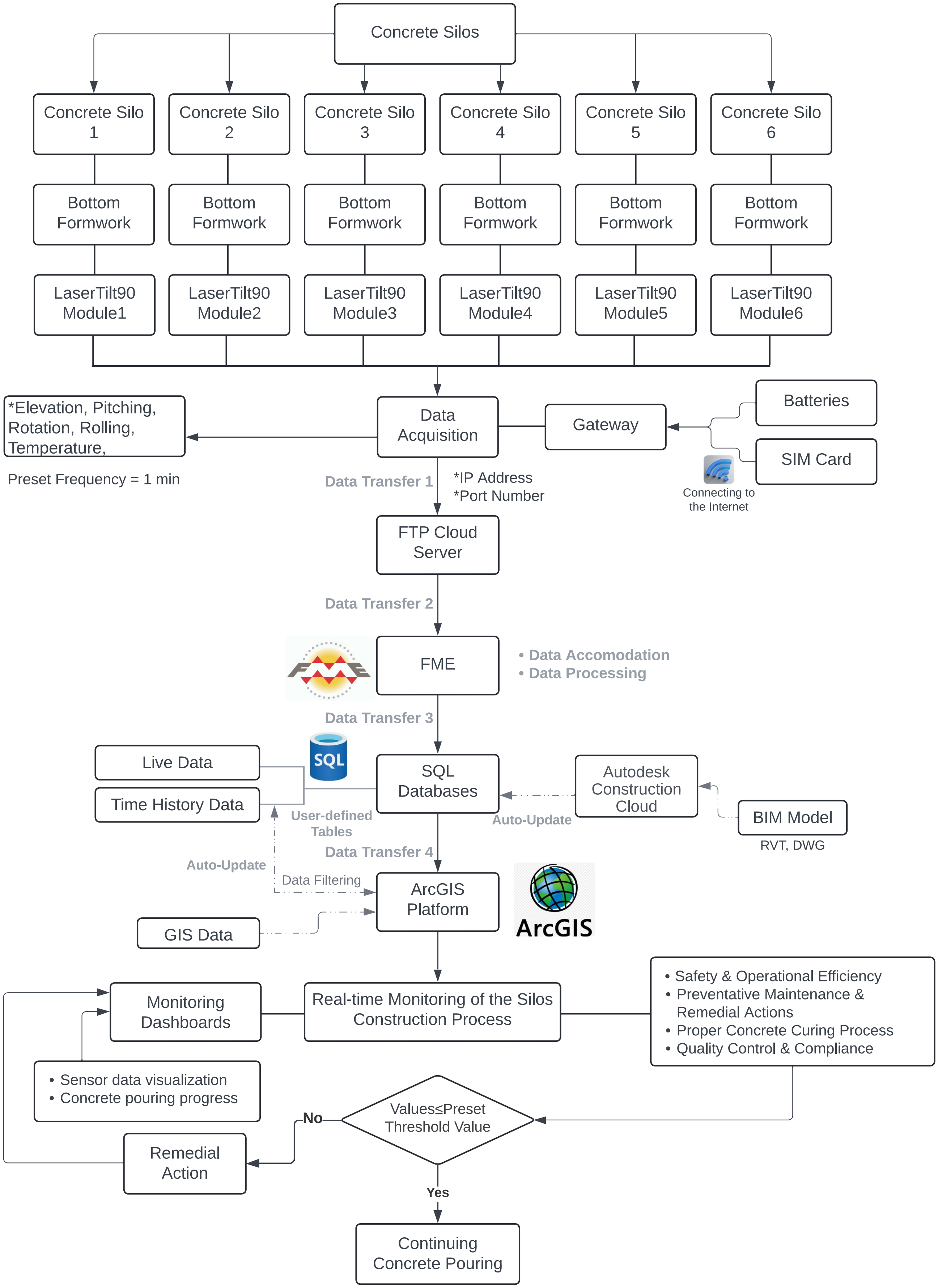


**Fig. 3.** Detailed architecture of the developed system.

**Fig. 4.** LaserTilt90 module. (Reprinted with permission from Worldsensing 2023.)

- Swivel mounting bracket (WS-ACCLAS-NSB): A swivel mounting bracket was used to securely attach the LaserTilt90 modules to the formwork's horizontal surface, ensuring stability and precise alignment during construction monitoring.

A gateway equipped with a SIM card was installed on site to facilitate data communication. The sensors utilized ultrahigh frequency (UHF) to transmit data to this gateway for wireless transmission, enabling high-bandwidth data transfer, which was essential for real-time monitoring applications requiring rapid updates. The gateway relayed collected data to a designated host server. In this study, a FTP cloud server was employed due to its pre-existing setup for surveying purposes. The FTP server served as the primary data repository, where sensor readings, including elevation, pitch, roll, rotation, and temperature, were continuously uploaded and processed. Fig. 4 shows the LaserTilt90 module.

### Data Transfer and Processing

As illustrated in Fig. 3, the system framework involves four data-transfer steps critical for the process flow. The first data transfer sends sensor data to the FTP server. Subsequently, the second data transfer moves the data from the FTP server to the FME server. The third step involves transferring data from the FME server to the SQL server. Finally, the fourth data transfer relays sensor data from the SQL server to the ArcGIS platform, which is used for data analysis and visualization. The data are processed and transformed at each step into the appropriate format for use in the subsequent phase. The data processing workflow involves two key components: a Python script and a FME Server workflow, each developed for handling different aspects of the data management process.

The Python script connects to a FTP server to download and process data files related to silo operations. It extracts unique identifiers from the filenames, assigns specific geographic coordinates and silo names, and organizes the data into a structured data frame. The script enriches the data with time-stamped information, renames columns for clarity, and sorts the data by time, ensuring readiness for further analysis.

Complementing this, the FME Server workflow automates the retrieval and processing of spatial and nonspatial data. It begins by fetching data from SharePoint, standardizing attributes, and managing them through various transformers. The workflow includes a change detection step to compare data sets, filtering and counting records, and ultimately saving the processed data to designated outputs for both current and historical records.

Together, these tools create a robust system for managing and analyzing data, ensuring that data are accurately processed, organized, and stored for further use.

### Data Storage

Data are maintained on two cloud servers, specifically the FTP and SQL servers, throughout the entire process. As described in the previous section, two distinct tables, namely, the Live Data table (SILO) and Time History Data table (SILO_HIST), were configured on the SQL server to manage data transferred from the FTP server via an automated workflow developed on the FME platform. Sensor data, captured every minute, are initially transferred to and stored in the SILO table, which continuously updates with the latest data collected from the sensors. This table ensures that the most recent construction parameters are readily available for real-time monitoring and decision-making. To preserve historical data, each new update is also copied into the SILO_HIST table, which serves as a structured archive containing all previously recorded measurements throughout the project. To ensure data consistency, SILO and SILO_HIST maintain a one-to-many relationship, where the Name attribute serves as the primary key in the live table (SILO), linking each real-time data entry to its corresponding historical records. This schema facilitates accurate trend analysis, enabling project teams to compare past and present conditions while ensuring data integrity over time.

Consequently, both SQL tables are automatically updated every minute. The BIM model was also imported into the SQL server for visualization in the next step. Fig. 5 illustrates the SQL Live Data table and the associated query.

### Data Visualization

The data visualization process is conducted on the ArcGIS platform, which integrates information from the SQL server, including the BIM model, the sensor data tables, and the geographical information of the construction site. This system connects ArcGIS to the BIM model, which is stored in a specific project folder on the ACC platform and imported into the SQL server, facilitating a comprehensive visualization approach. Three specially developed dashboards display a range of data to track the construction progress and the historical sensor data for silos, including details on concrete pouring.

The first dashboard, Progress Monitoring of Silos Construction, provided insights into the concrete pouring process, detailing the progress in terms of height and volume measured in cubic meters.



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```sql
SELECT TOP (1000) [OBJECTID]
      ,[Name]
      ,[Date_and_time]
      ,[Elevation]
      ,[Pitch]
      ,[Rotation]
      ,[Roll]
      ,[x]
      ,[y]
      ,[rownum]
      ,[Shape]
      ,[GDB_GEOMATTR_DATA]
      ,[Temperature]
  FROM [sde].[SILO]
```

% | Results | Spatial results | Messages

| OBJECTID | Name | Date_and_time | Elevation | Pitch | Rotation | Roll | x | y | rownum | Shape | GDB_GEOMATTR_DATA | Temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Silo1 | 2023-05-18 08:06:00.0000000 | 44.29030000 | -0.11670000 | -0.34530000 | -0.38660000 | -71.81495700 | 46.74456300 | 1 | 0xE6100000010D5DA9674128F451C0E46723D74D5F4740B00... | NULL | 13.40000000 |
| 2 | Silo7 | 2023-05-18 08:06:00.0000000 | 68.79000000 | 0.27220000 | -0.23840000 | 0.33020000 | -71.81517500 | 46.74464500 | 1 | 0xE6100000010D1361C3D32BF451C0A1100187505F4740C3F... | NULL | 4.40000000 |
| 3 | Silo3 | 2023-05-18 08:03:00.0000000 | 68.75860000 | -0.03660000 | 0.10490000 | 0.09850000 | -71.81535000 | 46.74447200 | 1 | 0xE6100000010DCA32C4B12EF451C0D464C6DB4A5F4740B8... | NULL | 3.80000000 |
| 4 | Silo5 | 2023-05-18 08:03:00.0000000 | 23.81670000 | -0.23140000 | 0.17880000 | -0.05160000 | -71.81529700 | 46.74459500 | 1 | 0xE6100000010DB9E177D32DF451C0EFE192E34E5F4740A9... | NULL | 6.70000000 |

**Fig. 5.** SQL Live Data table accommodating sensor data at each time interval.

The second dashboard, IoT Sensors Monitoring Silos, offered real-time updates every minute on six silos, including data on date, elevation, temperature, rotation, pitch, and roll. Finally, the Silos_IoT Progress Charts dashboard provided a historical perspective on the IoT sensors' data throughout the monitoring period.

These dashboards were continuously refreshed from the SQL database, allowing for real-time monitoring and sophisticated analysis, thereby enhancing the management and visualization of the construction progress.

## Application on Site

The components described in the previous section were developed to introduce a system workflow that visualized and updated the IoT sensors' data in the cloud at regular intervals. This system also integrated these updates with the BIM model and modified the specified installation status BIM parameter. This functionality was crucial for monitoring the progress and quality of the concrete silos' construction process.

The LaserTilt90 DAQ system was programmed to transmit data on elevation, pitch, roll, rotation, and temperature to the FTP server at each designated time interval. An automated workflow on the FME server retrieved this data from the FTP server to update the Live Data table and its parameters in the MySQL server. Additionally, a query in the MySQL server was executed to duplicate the Live Data table into the Time History Data table at each interval, ensuring a continuous and updated record of the construction's progress and sensor readings.

The monitoring took place in May 2023. At each designated time interval, the system recorded one data point for elevation, pitch, rotation, roll, and temperature, collecting thousands of data points for each monitoring parameter over the period. These data points were transmitted to the FTP cloud server at each interval and automatically transferred to and updated in the Live Data table, which was developed in the MySQL server. A specific workflow created in the FME server facilitated this data-transfer and update process.

Data from the Live Data and Time History tables in MySQL were imported into the ArcGIS Map tool to integrate with the GIS data and the BIM model simultaneously. This integration facilitated effective and efficient monitoring of the construction progress and accuracy. Four specially developed dashboards, described in the previous section, displayed a variety of data that tracked both the construction progress and historical sensor data for silos.

Fig. 6 shows the Progress Monitoring of Silos Construction dashboard, which tracked the construction progress of the silos in terms of height and volume after each update. The dashboard provided a comprehensive view of the construction progress for multiple silos over time. In Fig. 6(a), as of May 12, 2023, at 3:00 a.m., the dashboard indicated a 19% progression in height and an approximate concrete volume of 132 $m^3$ for the silos, with a construction rate of 8.9 $m^3/h$. Fig. 6(b), as of May 13, 2023, at 11:00 a.m., shows significant progress with the height reaching 64% and the concrete volume approximating 560 $m^3$, at an improved rate of 12.4 $m^3/h$. These visualizations, combined with a detailed list of projects and operations, enabled precise tracking and management of the construction activities, highlighting both real-time and cumulative progress in an intuitive, color-coded three-dimensional (3D) model.

Fig. 7 displays the IoT Sensors Monitoring_Silos dashboard, which provides a comprehensive overview of the real-time monitoring data for three silos, displayed on an aerial map for spatial context. The boxes displayed in this figure correspond to the positions of IoT sensor nodes installed on the silos for monitoring key construction parameters. Each silo's panel presents specific metrics such as elevation, temperature, rotation, pitch, and roll recorded at precise time stamps. For instance, Silo 1 had an elevation of about 12.35 m and a temperature of 18.4°C, whereas Silo 2 showed slightly lower elevation and temperature values. The data indicate variations in rotation, pitch, and roll across the silos, highlighting structural dynamics and environmental conditions affecting each silo differently. This detailed visualization allows for effective monitoring and quick identification of any deviations or anomalies in the construction process, ensuring timely interventions to maintain structural integrity.

Finally, Fig. 8 displays the Silos_IoT Progress Charts dashboard, which shows a historical perspective on the IoT sensors' data throughout the monitoring period. The graphs illustrate the monitoring data for the Silo 7 over a period of time, focusing on key parameters such as rotation, elevation, pitch, roll, and temperature. The Rotation Progression over Time graph [Fig. 8(a)] shows fluctuations with no clear upward or downward trend, indicating variable rotational stability. The Elevation (m) Progression over Time graphs [Fig. 8(d) and top center] depict a consistent increase in height, suggesting continuous construction progress. The Pitch Progression over Time graph [Fig. 8(b)] reveals significant variations, indicating changes in the tilt angle, which could impact structural alignment. The Roll Progression over Time graph [Fig. 8(c)] also shows variability, reflecting changes in the silo's horizontal

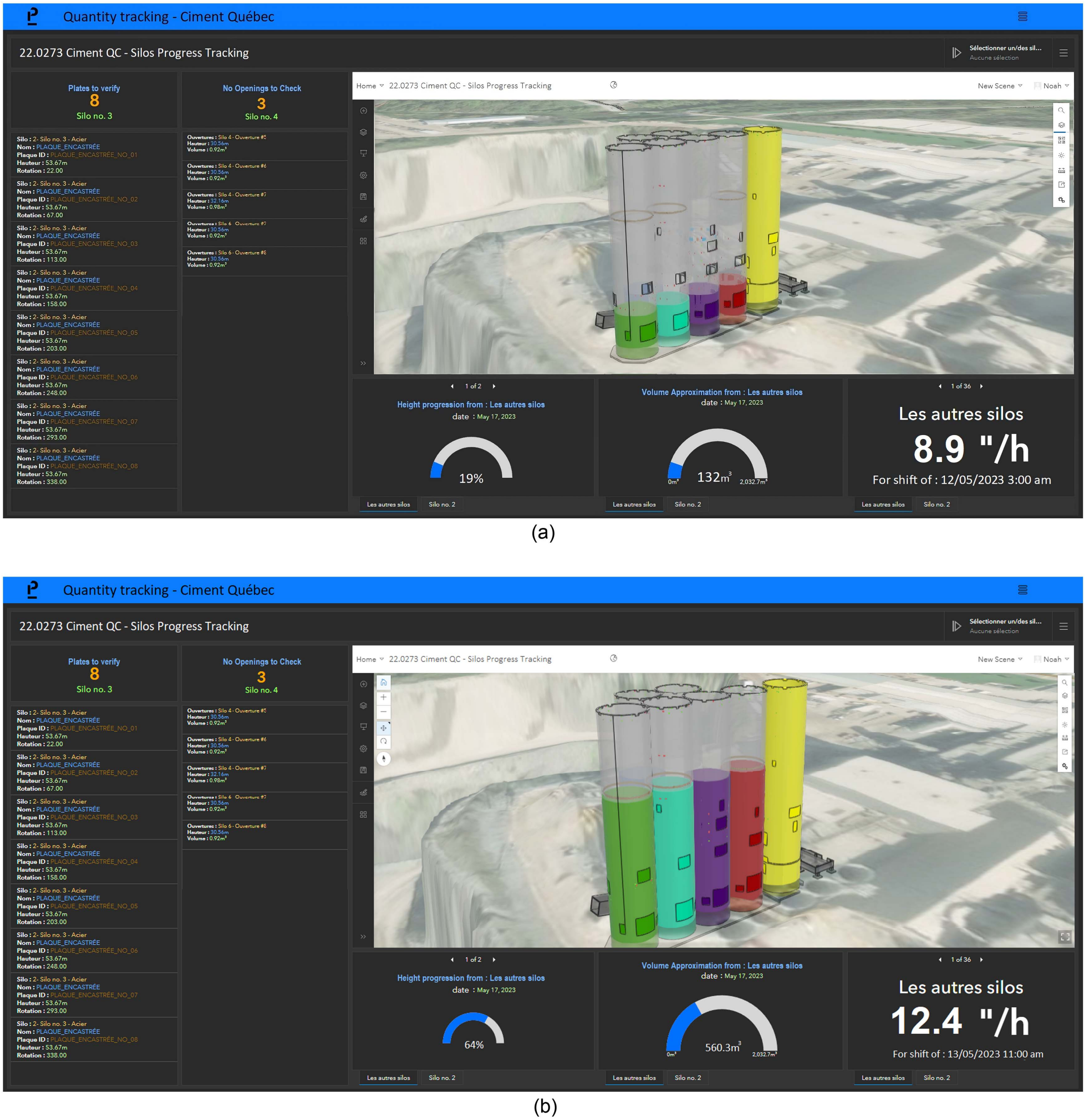


**Fig. 6.** Progress Monitoring of Silos Construction dashboard developed on the ArcGIS platform.

orientation. Lastly, the Temperature Progression over Time graph [Fig. 8(e)] displays fluctuations, possibly due to environmental conditions or the curing process of the concrete. Overall, the data indicate dynamic changes in the silo's structural parameters, necessitating continuous monitoring to ensure stability and quality throughout the construction process.

## Results and Validation Metrics

The DTC system, integrating BIM, IoT, and GIS, significantly enhanced construction efficiency, accuracy, and sustainability in the construction of six 45-m-high concrete silos at Ciment Québec. By continuously monitoring elevation, pitch, roll, rotation, and temperature, the system improved process control, ensuring precise alignment, optimized material usage, and real-time corrective actions. To assess the system's impact, key performance indicators (KPIs) were defined, focusing on the following aspects:

- Construction time reduction to evaluate planned versus actual project completion.
- Material efficiency to assess material usage against initial estimates.
- Structural stability to monitor deviations in formwork alignment.

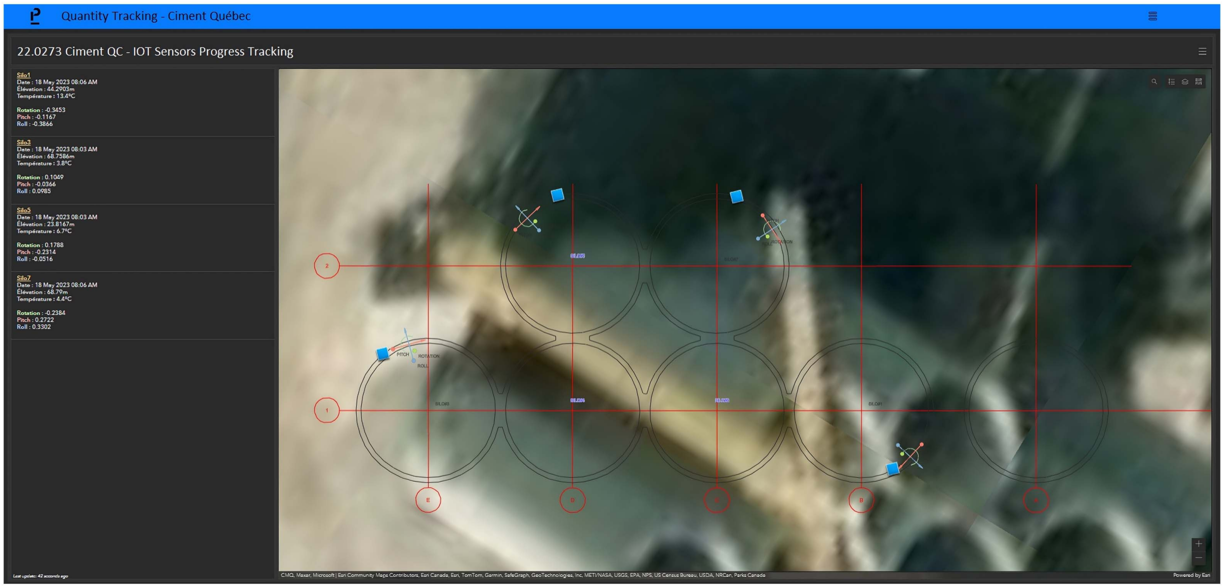


**Fig. 7.** IoT Sensors Monitoring_Silos dashboard developed on the ArcGIS platform.

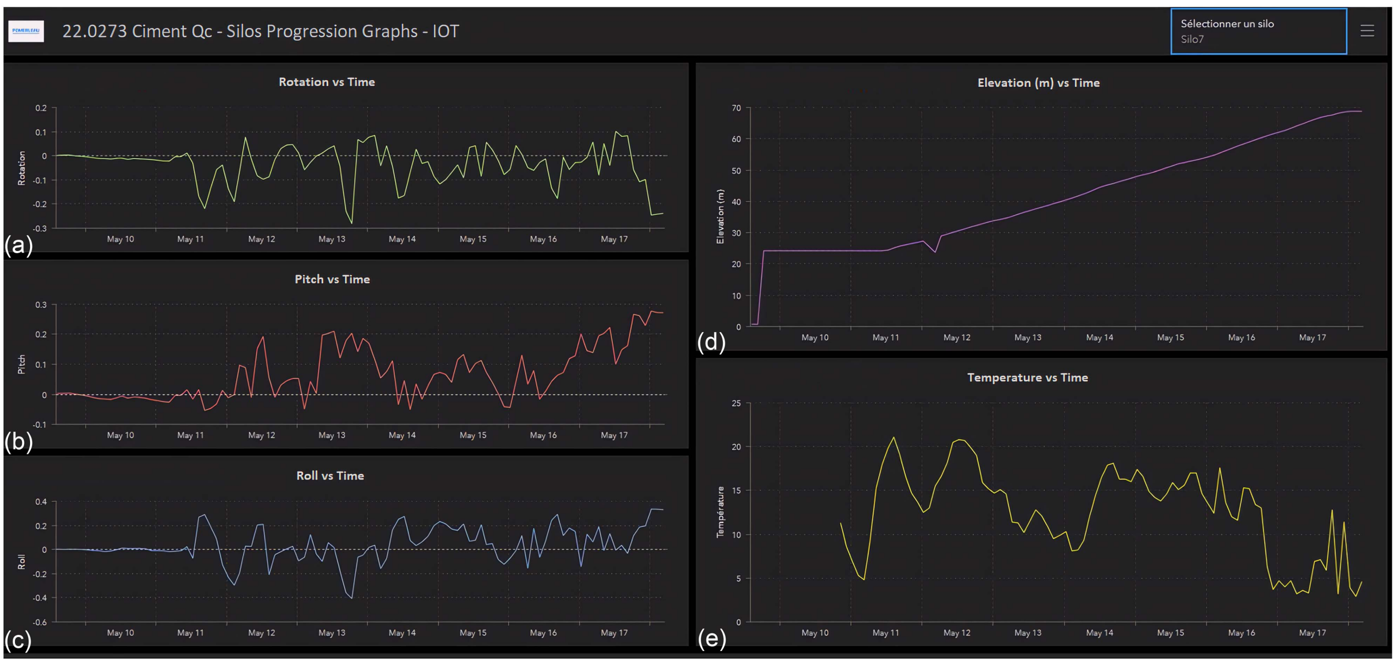


**Fig. 8.** Silos_IoT Progress Charts dashboard developed on the ArcGIS platform.

- Temperature monitoring to ensure optimal concrete curing conditions.
- Decision support and workflow efficiency to track real-time data utilization in project management.

## Real-Time Monitoring and Construction Accuracy

Accurate elevation tracking during slip-forming was essential to ensuring that the concrete silos were built according to design specifications. LaserTilt90 IoT sensors continuously measured elevation at predefined intervals, transmitting data every minute to the SQL Live Data table. This automated data flow enabled real-time progress tracking on the Progress Monitoring of Silos Construction dashboard. As of May 13, 2023, the dashboard indicated a 64% completion in height, with a total concrete volume of approximately 560 $m^3$ and a pouring rate of 12.4 $m^3/h$. Earlier, on May 12, 2023, at 3:00 a.m., the system recorded 19% completion, with a concrete volume of 132 $m^3$ and a pouring of 8.9 $m^3/h$.

By comparing planned versus actual height in real-time, construction teams detected and corrected deviations immediately, ensuring structural consistency and minimizing errors. Compared with traditional monitoring methods, which rely on manual inspections and periodic surveys, the DTC system enabled immediate feedback, allowing faster decision-making and reducing costly rework. The ability to cross-check BIM design parameters against real-time site conditions further enhanced construction accuracy and minimized schedule delays.

### Structural Stability and Formwork Alignment

Maintaining vertical alignment and preventing rotational deviations were critical challenges in slip-forming. IoT sensors embedded in the formwork continuously monitored pitch, roll, and rotation, transmitting data every minute to the SQL database and ArcGIS platform. The IoT Sensors Monitoring_Silos dashboard provided real-time alerts for any structural misalignments, allowing for immediate adjustments. Silo 1 had an elevation of 12.35 m and a temperature of 18.4°C, whereas Silo 2 showed slightly lower elevation and temperature values. The Silos_IoT Progress Charts dashboard displayed historical pitch, roll, and rotation trends, enabling teams to monitor stability over time and detect minor structural shifts before they escalated.

By automating the detection of rotational drifts and misalignments, the system ensured continuous alignment corrections, preserving the structural integrity of the silos.

### Temperature Monitoring and Concrete Curing Optimization

To ensure optimal concrete curing conditions, a thermocouple sensor was deployed alongside the LaserTilt90 modules. This additional sensor measured the ambient temperature and ensured that the curing process remained within optimal parameters. The temperature data were automatically transmitted to the SQL database and displayed in ArcGIS dashboards, allowing project managers to adjust curing conditions as needed. Historical data indicated temperature fluctuations over time, which helped optimize curing conditions and prevent premature drying or excessive moisture retention that could compromise the strength and durability of the silos.

This real-time temperature tracking allowed construction teams to adapt their curing strategy dynamically, leading to higher concrete quality and durability.

### Construction Time Reduction and Productivity Enhancement

The DTC system enabled a 28% reduction in construction time, significantly improving productivity and schedule reliability. Initially planned for 9 days, the concrete pouring phase was completed in just 6.5 days due to automated monitoring and predictive decision-making. The real-time dashboards facilitated better coordination of materials, labor, and equipment, preventing workflow disruptions. The continuous slip-forming process, monitored and adjusted in real-time, eliminated unnecessary stoppages, ensuring an uninterrupted workflow.

Compared with previous similar projects without DTC integration, workflow inefficiencies often led to unplanned delays due to misalignment corrections, material inconsistencies, and uncoordinated resource allocation. The ability to automatically compare BIM design parameters with real-time field data resulted in faster decision-making, fewer errors, and reduced rework costs.

### Material Usage Optimization and Waste Reduction

By precisely tracking steel plate positioning and minimizing material overuse, the system contributed to a 15% reduction in material wastage. IoT-based real-time monitoring ensured that formwork and reinforcements were positioned accurately, preventing excess material consumption. In conventional construction, deviations in steel positioning often led to corrective work, increasing material waste. The automated monitoring of slip-forming parameters allowed for immediate adjustments, avoiding unnecessary material losses and improving sustainability.

### Decision Support and Workflow Coordination

The system improved real-time communication and coordination across a 120-person workforce operating in 12-h shifts. The ArcGIS dashboards provided color-coded status updates, allowing teams to quickly interpret progress and minimize shift transition errors. Automated updates from the SQL database ensured that all team members had access to the latest project data. This eliminated delays in information transfer, improved workflow synchronization, and enhanced decision-making efficiency.

The system fostered seamless collaboration, ensuring that shift transitions were smooth, work progress was continuous, and operational bottlenecks were minimized.

### Economic Justification and Return on Investment

Despite the initial investment required for IoT devices, software integration, and staff training, the long-term financial benefits significantly outweighed these costs. The 28% reduction in construction time resulted in lower labor and equipment costs. The 15% reduction in material waste minimized procurement expenses. Also, the ability to make real-time decisions reduced costly rework, further improving project profitability. Compared with traditional construction projects, where errors often escalate costs, this case study demonstrates that DTC integration improves financial feasibility and return on investment (ROI).

## Discussion

The implementation of an integrated DTC system for real-time monitoring of construction parameters using BIM, IoT, and GIS technologies presents a significant technological advance in the construction of concrete silos. This discussion evaluates the effectiveness of the system components, highlights the challenges encountered, explores the broader implications for the construction industry, and explains the rationale behind the choice of platforms and tools used in this study.

The integrated system's ability to monitor critical parameters such as pitch, roll, rotation, elevation, and temperature in real-time was instrumental in ensuring the structural integrity and precision of concrete silo construction. The use of LaserTilt90 DAQ systems to collect and transmit data to a FTP server, followed by the automated workflows in FME for data processing and transfer, illustrates a seamless integration of advanced technologies. The continuous updates to the SQL database and subsequent visualization through ArcGIS dashboards provided a comprehensive and intuitive monitoring solution.

Several specific platforms and tools were chosen for their unique capabilities and advantages. The LaserTilt90 DAQ systems were selected for their precision in measuring critical parameters, which are vital for the stability and quality of slip-formed concrete structures. The FTP server was used for its reliable data storage and transfer capabilities, ensuring sensor data could be efficiently transmitted from the construction site to the processing systems.

The FME software was employed to automate the data transfer and processing tasks due to its robustness in handling various data formats and its powerful automation capabilities. This allowed for seamless integration of sensor data into the SQL database, where Microsoft Azure SQL databases were used for their scalability, security, and ease of access. The SQL databases provided a reliable



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platform for storing live and historical data, which were essential for continuous monitoring and analysis.

ArcGIS was chosen as the visualization platform for its advanced spatial analysis capabilities and its ability to integrate GIS data with BIM models. The ArcGIS dashboards enabled real-time visualization of construction progress and sensor data, providing an intuitive interface for monitoring and decision-making. This integration facilitated effective and efficient management of construction activities, ensuring that the project stayed on track and met quality standards.

The dashboards provided real-time tracking of construction progress, improving project management and decision-making. However, integrating BIM, IoT, and GIS technologies proved challenging. Data interoperability between these systems remains a significant problem, as noted in the "Literature Review." The complexity of merging parametric data from BIM with geospatial data from GIS and dynamic data from IoT devices requires robust data management and processing frameworks. The FME software addressed some of these challenges through automated data transfers and updates, but further research and development are needed to enhance interoperability and streamline data integration processes, so that DTC systems can be implemented more easily in the future.

The case study on the construction of six 45-m-high concrete silos at Ciment Québec showcased the practical application of this system. Construction duration was reduced by 28%. The dashboards provided valuable insights into the construction process and contributed to managers' ability to ensure structural integrity and prevent deviations. These visualizations significantly improved coordination and enabled timely interventions, contributing to overall safety and quality during construction. Notwithstanding these benefits, the study revealed the costs and challenges of adopting these advanced technologies in the construction industry. The initial setup and maintenance of IoT devices, data-transfer systems, and visualization tools require substantial investment and technical expertise. Additionally, the reliance on cloud-based servers for data storage and processing raises concerns about data security and reliability, necessitating the implementation of robust cybersecurity measures.

The case study is novel in that it is a pioneering example of a closed-loop DTC system as envisaged by Sacks et al. (2020). It goes beyond measurement of progress using integrated BIM and IoT systems as described in previous works (e.g., Shen 2022; Sarkar et al. 2023; Lokshina et al. 2019), by providing dashboards that directly support ongoing pull production control for workers and materials, quality control, and safety management. In comparison with existing research on digital twin applications on construction sites, which primarily emphasized technology for monitoring safety risks and hazard detection (Teizer et al. 2022; Shariatfar et al. 2022), this study broadens the scope by implementing a fully integrated DTC system that combines BIM, IoT, and GIS to enhance efficiency and resource management. Unlike previous studies that often highlighted the unresolved challenges of cost and technical scalability in DT implementation (Jahagirdar and Leicht 2023; Abugu et al. 2024), this case study addressed these barriers by demonstrating a practical, scalable application. Through automated data workflows and real-time monitoring, the DTC system enabled quantifiable improvements in project completion time, showcasing its potential for broad adoption on large-scale projects. This expanded functionality demonstrates the viability of the DTC concept as a comprehensive solution for both operational efficiency and safety management (Sacks et al. 2020).

The findings demonstrate that implementing DTC systems, although requiring initial investment and technical expertise, offers substantial long-term benefits regarding construction efficiency, precision, and management. The study highlighted the feasibility of integrating BIM, IoT, and GIS technologies to create comprehensive, real-time monitoring frameworks capable of handling complex construction processes like slip-forming. The utility of DTC systems in improving project coordination, reducing material wastage, and ensuring structural integrity underlines their value in large-scale construction projects. Additionally, the scalability and adaptability of the system make it applicable to a wide range of construction projects, from industrial to infrastructure sectors. These results suggest that DTC systems have the potential to become industry standards, especially as construction projects continue to grow in complexity and require more advanced management tools.

However, although the study has demonstrated the effectiveness of the DTC system, certain limitations must be acknowledged. One key limitation is the absence of a direct control group or baseline comparison of a similar project executed without the DTC system. Although the time and cost savings observed in this study suggest a substantial impact, a more rigorous validation approach, such as parallel project comparisons or simulation-based assessments, would strengthen these findings. Additionally, external factors such as variations in workforce efficiency, unexpected weather conditions, and supplier delays may have influenced project outcomes, making it challenging to isolate the precise contribution of the DTC system alone. Future studies should consider controlled experimental designs or data-driven benchmarking across multiple case studies to refine the assessment methodology and validate broader applicability.

## Conclusions

This case study presented a comprehensive framework integrating BIM, IoT, and GIS to enhance the construction process of concrete silos. Successfully implemented and tested on the Ciment Québec project in Canada, the system demonstrated significant improvements in construction efficiency, precision, and accuracy.

By continuously monitoring elevation, pitch, roll, rotation, and temperature using LaserTilt90 DAQ systems, combined with FME for data processing, Microsoft Azure SQL databases for storage, and ArcGIS for visualization, the system enabled seamless data integration, real-time decision-making, and immediate corrective actions, ensuring the structural integrity and quality of the concrete silos.

The implementation of the DTC system led to measurable benefits, including a 28% reduction in construction time, which directly lowered labor and equipment costs, and a 15% decrease in material wastage, attributed to the precise positioning of steel elements and continuous monitoring of slip-forming parameters. These reductions were made possible by real-time data-driven adjustments, ensuring that deviations were corrected before they caused delays or rework. The system also enabled a more efficient coordination of resources, with digital dashboards providing instant visibility into progress, allowing teams to optimize scheduling, prevent delays, and ensure smooth workflow execution.

Despite its success, several challenges were encountered in implementing this system. The initial setup costs, including sensor deployment, software integration, and specialized staff training, were substantial. Ensuring data interoperability between BIM, IoT, and GIS required custom workflows, adding to the system's complexity. Additionally, network dependency posed a challenge because stable internet connectivity was required for real-time updates, and occasional sensor calibration issues impacted data accuracy,



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requiring periodic adjustments. Addressing these factors is critical for scalability and broader adoption of DTC systems in construction projects.

The long-term advantages of this integrated system justify the investment. Reduced construction time and material usage translate into significant cost savings and environmental benefits. Furthermore, the enhanced project management capabilities, provided by real-time data and comprehensive visualization tools, allow for more efficient resource allocation and improved decision-making processes. These long-term benefits underscore the value of adopting advanced digital technologies in construction projects.

The deployment of this system provided valuable insights that can guide future implementations. The automation of monitoring and data-driven decision-making significantly reduced human error, improving overall construction accuracy. Integrating BIM, IoT, and GIS technologies proved highly effective in enhancing visibility and control over project execution, enabling construction teams to detect and address discrepancies in real-time. Standardizing data formats improved interoperability, ensuring smooth communication between different platforms. Additionally, adopting edge computing could further enhance real-time processing while reducing reliance on cloud-based networks, mitigating connectivity limitations. A phased implementation approach allowed teams to adapt progressively, increasing acceptance and usability on site.

The findings of this study suggest that the DTC system has strong potential for broader industry adoption, particularly in large-scale infrastructure projects where real-time monitoring and predictive analytics can significantly improve construction efficiency and safety. The system's scalability allows it to be applied to other types of construction, including bridges, highways, and industrial facilities. Expanding the use of GIS for dynamic risk assessment could further enhance construction site management by enabling real-time geospatial monitoring and proactive decision-making. The integration of digital twin technology can also be explored for long-term maintenance, predictive analytics, and performance optimization of built infrastructure.

Although the DTC system demonstrated significant improvements in efficiency, material savings, and quality control, assessing its ROI remains crucial for widespread industry adoption. Although the initial investment was substantial, the long-term financial benefits far outweighed these costs, as demonstrated by the reduction in labor and equipment expenses, minimizing material waste, and fewer costly rework instances. The direct correlation between real-time monitoring and construction efficiency underscores the value of digital integration in optimizing construction workflows. Future research should explore cost–benefit analyses across multiple project types to validate the economic feasibility of DTC adoption on a larger scale.

By addressing the challenges of data interoperability, investment costs, and cybersecurity, and continuing to refine its capabilities for broader industry applications, DTC systems can set a new standard for construction efficiency, sustainability, and precision. The long-term impact of integrating BIM, IoT, and GIS in construction workflows presents a transformational shift toward modernized, data-driven, and highly automated construction processes. This study demonstrated the potential of DTC as an innovative, scalable, and impactful solution for improving construction performance, resource utilization, and overall project outcomes, paving the way for its wider adoption across the construction industry.

In conclusion, the integration of BIM, IoT, and GIS within a real-time monitoring system offers a transformative approach to construction project management. This study provided strong evidence of the effectiveness of DTC systems in reducing project duration, minimizing material waste, and improving construction quality through data-driven decision-making. Although challenges related to cost, data interoperability, and system scalability remain, the long-term benefits significantly outweigh these initial barriers. Future research should focus on refining the technology, expanding its applicability to other construction domains, and further analyzing its economic impact. As the construction industry moves toward increased automation and digitalization, DTC systems are poised to become a critical tool in optimizing project efficiency, sustainability, and overall performance.

## Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request. Due to project confidentiality and proprietary agreements, certain data sets may be restricted from public dissemination. Researchers interested in accessing the data are encouraged to contact the corresponding author for further information.

## Author Contributions

Mojtaba Valinejadshoubi: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Supervision; Validation; Visualization; Writing – original draft; Writing – review and editing; Software. Rafael Sacks: Conceptualization; Methodology; Writing – review and editing. Fernando Valdivieso: Project administration; Resources. Charles Corneau-Gauvin: Project administration; Resources. Armel Kaptué: Software.

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