# Integration of BIM and RFID-Sensing for Automated Prefabrication and Progress Monitoring in Modular Construction

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**Abstract**

**Modular construction represents a significant advancement in the architectural, engineering, and construction (AEC) domain, bolstering productivity by integrating factory-based manufacturing and efficient assembly techniques. This study presents a holistic approach, merging Building Information Modelling (BIM) with technological automation interoperability, to facilitate seamless prefabrication and automatic monitoring within modular construction projects. It underscores the importance of comprehensive management across the construction lifecycle, from prefabrication to final assembly. The research advocates for an integrated framework encompassing information identification, data mapping between Industry Foundation Classes (IFC) and ProgressXML (PXML), and semantic enrichment for Radio Frequency Identification (RFID) tracking. This approach is aimed at streamlining data exchange, automating fabrication processes, enhancing quality control, and optimizing precast supply chain management, thereby improving overall information management among project stakeholders.**

**Keywords –**
**Building Information Modeling, Progress Monitoring, Modular Construction, Industry Foundation Classes (IFC), ProgressXML (PXML), Radio Frequency Identification (RFID)**

## 1 Introduction

Modular construction integrates mass production and automated techniques to refine construction workflows, enhance workforce productivity, and promote environmental sustainability [7]. Building Information Modeling (BIM) functions as a digital tool that encapsulates both the physical and functional attributes of a building. It provides a comprehensive and evolving model that adapts continuously over the construction lifecycle. It has attracted considerable attention for its application in multiple fields of modular construction, including but not limited to design automation [3], automated manufacturing processes [2], the use of robotics in assembly [21], optimization of supply chain logistics [6], and the facilitation of a circular economy [1]. BIM functions as an object-oriented model that stores critical data for managing a building's lifecycle, covering aspects such as scheduling, analysis, and assessment.

In addressing the increasing demand for digital transformation within the modular construction sector, this study introduces an approach to bridge the digital-physical divide through the mapping of Industry Foundation Classes (IFC) and ProgressXML (PXML). IFC serves as the cornerstone for BIM interoperability, enabling seamless data exchange and management across various platforms. Meanwhile, PXML is tailored to represent the geometric and semantic details of prefabricated components, enhancing the flow of information for fabrication and logistics. This integration aims to automate and digitize the construction workflow, improving efficiency, quality control, and supply chain management. By ensuring data integrity and fidelity in the mapping process, this framework advances the digital management of information in modular construction, highlighting the potential of BIM and digital fabrication technologies to revolutionize construction processes, achieving higher efficiency and sustainability.

Managing the construction progress of precast components with BIM and sensing technologies streamlines the process from design to end-of-life.

Unique identifications in BIM model correspond to Radio Frequency Identification (RFID) tags on components, allowing real-time tracking through fabrication, storage, transportation and assembly [5]. Post-installation, real-time data in BIM supports maintenance scheduling and asset management. At the component's end-of-life, it assists in sustainable decommissioning practices. This integration enhances efficiency, reduces errors, and improves lifecycle traceability.

The conventional approach to construction progress monitoring, traditionally focusing on individual processes (including fabrication, temporary storage, fitting out, delivery, and installation), fails to align with the evolving global trends in modular construction. There is a growing need for an approach that integrates BIM to oversee the entire construction process, from factory-based production to site construction. Therefore, this paper introduces an innovative BIM methodology, enhanced by RFID-sensing technology, to facilitate automated construction progress monitoring, spanning from factory prefabrication to on-site assembly. We provide an illustrative example to demonstrate the effectiveness of these methods.

To assess the effectiveness of the suggested framework, field trials were conducted on a Prefabricated Prefinished Volumetric Construction (PPVC) residential project using RFID. Results confirmed the accurate on-site placement of precast units and the reliability of sensor-derived data.

# 2 Literature Review

## 2.1 Modular Construction

Modular construction, also known as offsite construction, prefabrication, or industrialized building system in literature, is commonly defined as a process in which building components or modules are produced in a controlled environment [9]. Different apart from traditional cast-in-place construction methods, modular construction is characterized by of standardization, industrialized production processes, and assembly-based construction [18]. Standardization in modular construction streamlines automation and improves construction progress. A notable obstacle is encountered when there is insufficient coordination and communication between the contractors and the precast suppliers [16]. Moreover, the complexity of managing congested construction sites with limited storage capacity underscores the importance of having access to item-level data for effective logistical coordination [20].

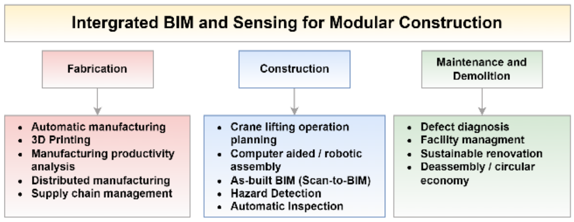


Figure 1. Integrated BIM and Sensing for Modular Construction

Figure 1 provides an overview of the integration of BIM and sensing application in modular construction, with illustrative contents to demonstrate the studies in different construction stages.

## 2.2 PXML For Automated Prefabrication

In the rapidly evolving field of modular construction, the integration of digital technologies has become paramount for enhancing efficiency and accuracy. Industry Foundation Classes (IFC), a universally recognized data schema integral to BIM, plays a crucial role in exchanging and managing construction and facility management data [17].

This study conducted interviews with three prefabricators from the Singapore Integrated Construction and Prefabrication Hub (ICPH). It was found that the PXML format, utilized for fabrication and enterprise resource planning, along with steel fabrication machine codes (BVBS) for reinforcement fabrication, are the predominant data formats employed in the contemporary precast fabrication industry. Liu, et al. [12] integrated BIM and steel fabrication machine codes (BVBS) using openBIM standards to streamline steel reinforcement design and prefabrication automation.

In IFC framework, the relationship and structural details of components are essential [14]. By converting this information into a unified data expression mode based on the IFC standard, the model's relevance and consistency are ensured [10]. This work focuses on enhancing the IFC framework specifically for precast entities. It involves refining attribute definitions and association links to accurately represent the characteristics and relationships inherent in prefabricated structures. This enhancement is key to achieving a detailed and precise description of the prefabricated model within the IFC standard system.

On the other hand, PXML offers a specialized format for capturing the geometrics and semantics of prefabricated components [8]. The strategic alignment of

IFC and PXML data structures paves the way for a more streamlined and cohesive workflow in precast fabrication. This alignment involves meticulous mapping of geometrical data, ensuring the physical characteristics of components are accurately represented, and semantic data integration, which encapsulates the functional attributes of these components. This study explores this data mapping of IFC and PXML in precast fabrication discipline, driving forward the construction industry towards a more digitized and efficient future.

### 2.3 Data acquisition for automatic construction progress monitoring

Problems with inadequately monitoring, finding, and recognizing highly tailored prefabricated components in supply chains for the construction industry include erroneous installations, double handling, and misplacement of parts, which cause delays in schedules and higher labor expenses [4]. Based on the previous research works, the data collection method for construction progress monitoring is categorized into enhanced information technology (IT) communication tools (emails, messages, etc.), Geo-spatial, 3D sensing and imaging technologies [13]. Since enhanced IT is not conducive to automated construction progress monitoring, this study summarized prior research and conducted the comparison of data acquisition methods as follows:

| Technologies | Features | Advantages | Disadvantages |
|---|---|---|---|
| **Geospatial technologies**<br>Barcodes and QR codes, RFID, UWB, GNSS | • Automated and efficient monitoring of construction sites;<br>• Efficient tracking of materials, inventory, construction progress and labour tracking; | • High capacity of data content and type;<br>• High reliability;<br>• Ease of production; | • Initial investment;<br>• Manpower in installation, scanning, and maintenance;<br>• Cannot efficiently indicate the progress of partially completed or operation-level tasks; |
| **3D Sensing technologies**<br>LiDAR Scanning | • Can avoid potential errors and can be adopted in structural health monitoring; | • Accurate method to capture real condition in construction sites; | • Slow warm-up time;<br>• A clear line of sight, noise from moving moving machinery and personal;<br>• Expensive device;<br>• Lack of portability; |
| **Imaging technologies**<br>Digital images, videos, depth images | • Examples for damage detection and safety evaluation;<br>• Automatically calculate the percentage completion and measure the progress; | • Cost-effective;<br>• Moderate accuracy and quality; | • Considerable time of computation;<br>• Sensitivity due to different lighting conditions;<br>• Line of sight; |

Figure 2. Comparison of Data Acquisition Methods

Geo-spatial sensing is chosen for its robust data capacity, reliability, and potential for seamless integration with precast supply chain management systems. Moreover, the collecting of real-time scheduling data can be enabled by BIM, and the monitoring of precast components during the whole processes is made possible by RFID and GNSS [11]. Recent research studies use IFC, a standard data schema for BIM model, to express monitoring data [19]. The differences between RFID and QR / Bar code [15] are summarized in Table 1.

Table 1 Comparison of RFID and QR/Bar Code

| RFID | QR / Bar Code |
|---|---|
| Around several meters | Close proximity |
| Writable, allowing data to be updated | Limited amount of data |
| More durable and can be used in harsh environments like construction sites. | Less durable in harsh environments and require a clear, unobstructed view to be scanned. |

These technologies mainly assist in identifying materials. Barcodes function through the line-of-sight scanning of specific patterns on materials. In contrast, passive RFID operates by using electromagnetic fields to detect and monitor tags affixed to items, eliminating the need for direct line-of-sight. Passive RFID system technology has been selected to as an essential connector, bridging BIM elements with the real-world components or modules of precast structures, owing to its cost-efficient nature, characterized by affordability, durability, and reusability/recyclability.

## 3 Methodology

This study initially identifies the critical information required for BIM-enabled progress monitoring in modular construction. Following this identification, the research proceeds with data mapping between IFC and PXML for precast prefabrication, and then integrates RFID technology for the tracking of precast components.

### 3.1 Information requirement

A BIM model for modular construction management should encompass various stages of the building process, from initial design to final decommissioning. Key information is categorized into different categories, including design information, manufacturing specifications, construction updates, maintenance records. The details are summarized in Table 2.

Table 2 Identification of information requirements

| Category | Description |
|---|---|
| **Design Information** | Detailed architectural, structural, and MEP designs for each modular component. |
| **Manufacturing Specifications** | Information about materials, fabrication processes, and quality control for module prefabrication. |
| **Transportation and Logistics Data** | Details on module transportation from manufacturing site to construction site, including size, weight, handling. |
| **Assembly and Installation Guidelines** | Instructions for on-site module assembly and installation, including assembly and connection details. |
| **Integration with Traditional Construction Methods** | Information on interaction between modular components and traditionally cast in-situ elements. |
| **Sustainability Features** | Data on environmental impact, energy efficiency, and waste reduction strategies. |
| **Operational and Maintenance Information** | Details on building operation and maintenance, including maintenance access and replacement schedules. |
| **Health and** | Safety procedures for handling and assembly |

| | |
|---|---|
| **Safety Protocols** | modular components. |
| **Cost and Time Estimates** | Detailed budgeting and scheduling information for the construction process. |
| **Future Disassembly and Reuse Plans** | Strategies for eventual module disassembly or recycling. |
| **Regulatory Compliance** | Ensuring designs and processes comply with relevant building codes and standards. |
| **Stakeholder Information** | Contact information and roles of all parties involved in the project. |
| **Change Management Data** | Records of any changes made during the project execution. |
| **As-Built Documentation** | Accurate as-built drawings and models reflecting the final state of the construction. |

### 3.2 Schematic Enrichment of BIM Data

#### (1) Mapping with PXML

According to IFC4.3.1.x (IFC4X3_ADD1), the majority of PXML-relevant data can be gathered from IFC files. Therefore, a mapping chart (Table 3) have been created to show the relation more clearly and accurately between the two data sets.

Table 3 Data Mapping for IFC and PXML

| PXML Element | PXML Attributes (Version 1.3) | IFC Entity (IFC4X3_ADD1) | Missing IFC Entity |
|---|---|---|---|
| **Global ID** | Unique identifier for each element | **IfcGloballyUniqueId** | |
| **DocInfo** | GlobalID, Document Version, Comment, ConvertConventions, Mode | **IfcDocumentInformation** | |
| **Order** | Order Information, Import Source Information, ApplicationName, ApplicationGUID, ApplicationVersion | **IfcWorkOrder, IfcApplication** | Missing specific IFC entity for Import Source Information |
| **Product (Element)** | ElementNo, ProductType, PieceCount, Comment, RotationPosition, Stacking Information, Project Coordinates, Supplementary Product Information | **IfcElement, IfcBuildingElement** | Missing specific entities for Double Walls and Project Coordinates |
| **ElementInfo** | Fields of ElementInfo entries, Predefined ElementInfo types, ElemInfoVal | **IfcElement, IfcPropertySet, IfcElementComponent, IfcBuiltElement** | No direct IFC entity for Predefined ElementInfo types; custom property sets may be required |
| **Slab (Element Part)** | PartType, Geometric Slab Placement, Slab Production Directives, Geometric Placement and Production Directives for Double Walls, Multi-Layer Elements, Legacy Slab Fields, Simplified geometry representation | **IfcSlab, IfcSlabType, IfcProductDefinitionShape, IfcShapeRepresentation** | Missing entities for Slab Production Directives and Multi-Layer Elements |
| **Outline** | Geometric Outline Placement, Height, Name, GenericInfo, MountingInstruction, MountPartType, MountPartArticle, MountPartProperties, Concrete Properties, Layer, ObjectID, Shape SVertex | **IfcObjectPlacement IfcLocalPlacement IfcMaterial, IfcBuildingElementProxy** | Missing entity for Simplified geometry representation |
| **Steel** | Geometric Steel Placement, ToTurn, StopOnTurningSide, Name, MeshType, WeldingDensity, BorderStrength, Generic Steel Info, Steel Production Directives, Layer, ObjectID | **IfcReinforcingBar, IfcReinforcingBarType, IfcReinforcingMesh, IfcShapeRepresentation** | No direct IFC entity for MeshType and WeldingDensity; possibly handled by IfcMaterialProperties |
| **Bar** | ShapeMode, ReinforcementType, SteelQuality, PieceCount, Diameter, XYZ, RotZ, ArticleNo, NoAutoProd, ExtIronWeight, Bin, Pos, Note, Machine, BendingDevice, Spacer, WeldingPoint, Segment, Canonical Bar representation | **IfcReinforcingBar, IfcReinforcingBarType IfcElementQuantity, IfcShapeRepresentation** | Missing detailed specification for ShapeMode and SteelQuality in IFC |
| **Girder** | PieceCount, XYZ, GirderName, Length, AngleToX, NoAutoProd, Height, TopExcess, BottomExcess, Weight, TopFlangeDiameter, BottomFlangeDiameter, GirderType, MountingType, ArticleNo, Machine, Period, Width, AnchorBar, GirderExt, Section | **IfcGrid, IfcGridPlacement** | No equivalent for GirderExt; custom extensions may be needed |
| **Custom PXML Element** | Custom attributes | | No direct IFC entity; custom mapping or extension required |

The openBIM standards together with some common BIM specifications are introduced in this research, and the parameters in the PXML specification are listed and parsed using the latest version of the IFC4.3.1.x schema in terms of the semantic content of the precast components. The data mapping between PXML standard and IFC schema is made to address missing information in IFC based on existing entities of building elements and incomplete conversion in order to make it easier to input information prefabrication machines and tracking system. The efficiency of fabricating will be greatly improved with the use of data mapping, which will also hasten the process' automation.

#### (2) Mapping with RFID


Figure 3. Association between physical object, IFC Unique ID and RFID EPC

After fabrication, each component is assigned a unique identifier which will be linked to its RFID tag. An algorithm has been developed to link the IFC Unique ID of building model objects with a corresponding Electronic Product Code (EPC) used in RFID systems. This integration allows for the automatic conversion between these two identifiers. When a task involves an object with an RFID tag, the system detects the EPC and translates it into the IFC Unique ID. This process enables precise identification and management of physical objects in the whole life cycle, ensuring real-time synchronization with their digital counterparts in the building information model, enhancing efficiency and accuracy in building management.

The RFID-enabled digital inventory and logistics management system, detailed in Table 3, is designed for efficient tracking and management of construction materials. It utilizes an RFID handheld scanner, adept at tracking materials from prefabrication to on-site delivery and installation, adapting to various logistic scenarios like temporary storage or return for repairs. Crucial for the dynamic construction environment, the scanner's mobility and versatility align well with site unpredictability.

Table 3 RFID-enabled Tracking Operations

| Phase | Operations |
|---|---|
| I. Production | Attach RFID tag after precast component is fabricated, associate RFID with BIM elements and select produced |
| II. Transportation (to warehouse or construction site) | Scan RFID tag at factory gate, transport precast component to construction site |
| | Scan RFID tag at factory gate, transport precast component to warehouse |
| III. Arrival (at warehouse or construction site) | Scan RFID tag on site, stockpiled on site storage area |
| | Scan RFID tag on warehouse, processed in fitting out yard |
| | Scan RFID tag on construction site/warehouse, return immediately to prefabricator due to quality issues |
| IV. Assembly | Deliver precast component to the assembly location on site, and scan RFID tag |

## 4 Case study

This study utilized a BIM Platform, serving as a centralized communication center for project communities, enabling collaboration and data exchange across construction processes and supply chains. It acts as the data backbone for the system, allowing access to object-based data and API, as demonstrated in Figure 4. In the context of BIM-enabled prefabrication and progress monitoring, an integrated BIM and RFID system is developed to track, monitor, and manage the flow of building materials. This system updates project stakeholders on material status, ensuring quick, simple, and trustworthy identification, recording, tracking, and sharing of material logistic information.

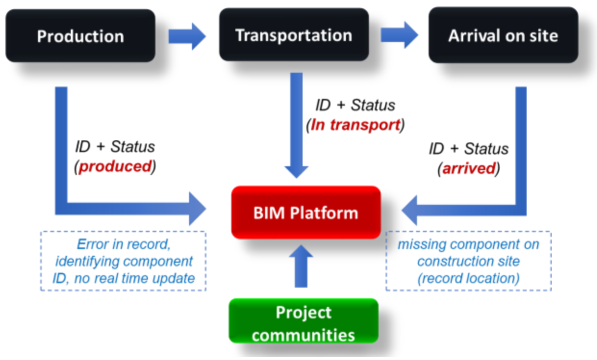


Figure 4 Smart Tracking System Framework

Project stakeholders in the construction supply chain can provide and obtain real-time information and project updates, enhancing budget and schedule management. The system reduces project failure costs and time through real-time monitoring, effective project management, and early schedule violation notifications. It coordinates planning errors, production, logistics, and assembly operations, preventing misunderstandings and avoiding rework and site readjustment.

Figure 5 illustrates the practical on-site RFID tagging and the association of RFID tags to precast elements. Passive RFID technology is chosen for cost-effective digital inventory and logistics management, supported by the BIM Platform. The system electronically manages construction inventory, reducing delays, increasing productivity, and preventing errors in deliveries.

Figure 5 Actual on-site implementation

The progress monitoring process involves attaching RFID tags to precast components after fabrication, associating them with BIM elements, and marking them as produced. Then the precast component will be shipped to warehouse or construction site, RFID tags are scanned at the factory gate, and components are transported to the construction site or warehouse. Upon arrival, RFID tags are scanned on-site or in the warehouse, with components either stockpiled on-site or processed in the fitting-out yard. Quality issues may prompt an immediate return to the prefabricator. During assembly, precast components are delivered to the assembly location on-site, and RFID tags are scanned. The locations and processes are illustrated in Figure 6.

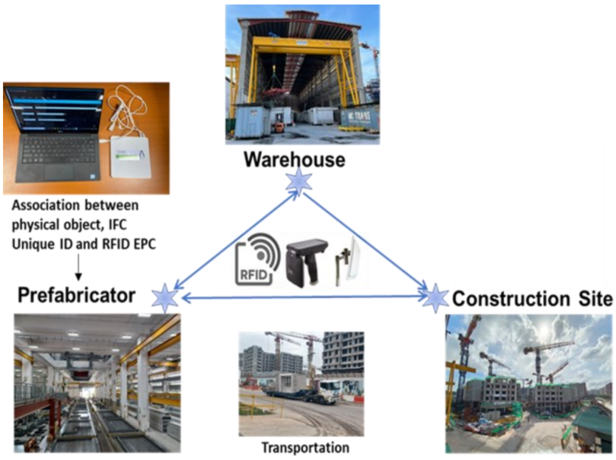


Figure 6 RFID tracking process and locations

This comprehensive process integrates RFID technology with BIM, allowing for real-time tracking and monitoring of precast components throughout their lifecycle. It enhances efficiency in logistics, quality control, and assembly operations, contributing to streamlined construction processes and improved project management. The seamless combination of RFID and BIM ensures accurate data exchange and facilitates effective communication across the construction supply chain, ultimately optimizing the overall construction workflow.

The dataset provides detailed information on construction assemblies, including identification, naming, location, status, production and installation dates, classification, and type, facilitating tracking and management within the construction project. The PPVC components are under IFCELEMENTASSEMBLY, indicating as integrated model for construction. The analysis of the precast modular production and installation dataset has revealed some critical insights and potential bottlenecks:

- The mean installation delay, calculated as the difference between the actual installation date and the planned production date, is approximately 280 days. This indicates a significant gap between when modules are planned to be produced and when they are actually installed.
- The standard deviation for installation delays is about 80 days, suggesting variability in how different modules experience delays.

To mitigate bottlenecks in construction projects, it is recommended to enhance project management by fostering improved coordination among production, logistics, and installation teams, thereby minimizing delays. Further, the supply chain should be analyzed and optimized to ensure the efficient delivery of modules from production facilities to installation sites.

Based on the analysis of the precast modular production and installation dataset, potential areas for future research include developing dynamic planning strategies to adapt to changing conditions, conducting uncertainty analysis to assess variability in processes, optimizing production workflows to minimize delays, enhancing supply chain integration, implementing real-time monitoring for proactive intervention, and devising risk management strategies to mitigate disruptions.

## 5. Conclusions and future work

This study demonstrates the interoperability of BIM with automation technologies, enabling prefabrication, and progress monitoring in modular construction. The incorporation of BIM enables the automated exchange of geometric and product data from the model, streamlining the prefabrication process. Additionally, BIM integration with an RFID-enabled digital inventory and logistics management system is implemented to oversee and trace the precast component's journey until its assembly on-site.

One limitation of this study on data mapping between PXML and IFC for precast fabrication is the potential complexity and variability of data structures between the two formats, which may require extensive effort and expertise to ensure accurate and comprehensive mapping. Additionally, discrepancies in data granularity and semantics could pose challenges in achieving seamless interoperability, potentially leading to inconsistencies or loss of information during the mapping process. Because different geometrical formulations are used for various forms of precast components, there are still some issues with the conversion of the geometry information in PXML. These issues might be addressed and resolved in the future along with further information about the IFC extension. The study plan also calls for testing the PXML code produced by the created Dynamo program in a nearby precast factory to ensure that it is valid.

To assess the effectiveness of the suggested framework, field trials were conducted on a PPVC residential project using RFID. Results confirmed the accurate on-site placement of precast units and the reliability of sensor-derived data. The research adopted an integrated methodology, enabling the real-time transmission of data to engineers for decision-making, thus optimizing workforce and resource distribution in modular construction. It is observed that integrating RFID data seamlessly into BIM platforms may require significant technical expertise and could pose challenges in terms of data synchronization and interoperability, especially when catering BIM design changes.

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