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Green Hydrogen for Heavy Industry

Green hydrogen, produced by electrolyzing water using renewable energy, offers a zero-emission alternative for decarbonizing hard-to-abate industrial sectors including steel, cement, and chemicals. With global production costs declining rapidly and project pipelines expanding, it is emerging as a critical clean energy carrier for achieving industrial net-zero targets.

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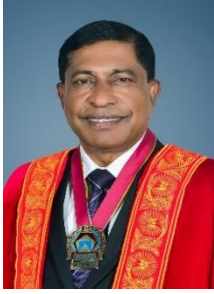
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Message from the President of IIESL



It is with great pleasure and a profound sense of pride that I pen this message for the January 2026 edition of our Technical Journal, marking our very first publication for the year. As the apex professional body representing Incorporated Engineers in Sri Lanka, the Institution of Incorporated Engineers, Sri Lanka (IIESL) remains steadfastly committed to fostering professional excellence, continuous development, and strict regulatory alignment.

In this regard, I must remind and encourage all our valued members to maintain and advance their professional status by registering with the Engineering Council of Sri Lanka (ECSL), which stands as the supreme statutory authorizing body regulating engineering practice in our country. Adherence to this framework ensures our collective credibility and aligns our operations securely with national benchmarks.

The publication of this Technical Journal serves as a powerful testament to our institution's unwavering capability to motivate, educate, and systematically upgrade the knowledge and skills of our fraternity. In an era defined by rapid technological disruptions, staying abreast of modern scientific trends is paramount to public safety and engineering efficiency.

I would like to highly commend the authors and researchers whose rigorous efforts and technical insights have brought this volume to life. Your intellectual contributions are the bedrock of our profession. Looking forward, as we journey through 2026, I eagerly anticipate future editions that explore a diverse spectrum of emerging technological topics, expanding our boundaries of innovation. May this journal serve as an inspiring catalyst for your professional growth and engineering journey ahead.

Eng. Ananda Gunawardana – FIIESL, MBA (Rajarata)
President – IIESL

Message from the Editor of IIESL



It is with great pleasure that I present this edition of the Journal of the Institution of Incorporated Engineers, Sri Lanka (IIESL), which brings together a collection of articles contributed by our members following a rigorous double-blind review process. The articles featured in this issue reflect the breadth of engineering practice, innovation, research, and professional management within the Sri Lankan context. The contributions in this volume demonstrate how engineers continue to respond to emerging challenges and opportunities through the application of technology, sound engineering principles, and innovative thinking. The topics addressed highlight practical solutions to contemporary issues, advancements in engineering systems, the adoption of digital technologies, and the continuous pursuit of improved efficiency, sustainability, safety, and project performance. Collectively, these articles provide valuable insights that can contribute to professional learning, knowledge sharing and informed decision-making across diverse engineering disciplines.

Beyond their technical significance, many of the ideas and experiences shared in these papers have implications for society at large. Engineering solutions ultimately serve communities, industries, and the nation, and the dissemination of professional knowledge plays an important role in supporting sustainable development and improving quality of life. The Institution greatly values the commitment of members who take the time to document their experiences, research findings, innovations, and lessons learned. Such contributions enrich the profession, create opportunities for peer learning, and help preserve valuable engineering knowledge for future generations. I encourage more members to actively participate in this endeavor by sharing their expertise through technical articles, case studies, and professional reflections.

On behalf of the Editorial Committee, I extend my sincere appreciation to all authors, reviewers, and contributors whose dedication has made this publication possible. I trust that readers will find the contents of this journal both informative and thought-provoking, and that the knowledge shared herein will inspire continued professional excellence and innovation within the engineering community.

Eng. Damitha Abeykoon – FIIESL, MSc (USJP), NDT (UOM)
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Eng. Nihal Sooriyarachchi – (MIIESL) is a Chartered Civil and Environmental Engineer with over 40 years of local and international experience. He is a Chartered Water and Environmental Manager (CIWEM, London) and an Honorary Life Member of IESL with Chartered status from ECSL. He served as Chairman of the Road Development Authority (2015–2019), leading key national projects including elevated highways in Colombo and the New Kelani Bridge. He also held senior roles at CECB and Lanka Sugar Company. Beginning his career in the Mahaweli Programme, he built strong expertise in project and stakeholder management and played a pivotal role in strengthening Sri Lanka’s highway construction industry.



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SECTION I

Data Pattern Conversion for Legalized Weighing: Interface Between Hiweigh X1 and Everest Instruments Monitoring System

Sri Lankan First

Best Article Section 1

Mr. Rajitha Liyanage

Abstract; In Sri Lanka's dairy and retail weighing sectors, cloud-based monitoring systems supplied by foreign vendors are increasingly adopted to support data logging, operational dashboards, and centralized visibility. However, only a limited number of weighing indicators are legally approved for trade by the Measurement Units, Standards and Services Department (MUSSD). This regulatory requirement creates a significant challenge, as many modern monitoring platforms are incompatible with MUSSD-approved local indicators, thereby restricting lawful adoption of advanced digital monitoring technologies.

This paper presents the design, implementation, and validation of a real-time data pattern conversion interface that enables a MUSSD-approved Hiweigh X1 weighing indicator to communicate seamlessly with an Everest Instruments monitoring system without modifying either device. An ESP32 microcontroller is employed as a protocol converter to decode RS232 serial data frames generated by the Hiweigh X1 and reformat them into Everest-compatible data structures. Electrical isolation and voltage level adaptation are achieved using a MAX3232 RS232-to-TTL interface to ensure safe and reliable operation in industrial environments.

The proposed system is evaluated through a continuous 48-hour field deployment at an operational dairy collection point. A total of 1,000 weight readings is captured and forwarded, achieving 100% numerical agreement between the indicator display and the monitoring system output. The average end-to-end data transmission delay is measured below 200 ms, with no packet loss or data corruption observed.

Key Words: Legal Metrology, Weighing Indicator, Data protocol conversion, ESP32, RS232 communication.

1.0 Introduction

Accurate and verifiable weight measurements are fundamental to fair trade practices in dairy collection, retail weighing, and industrial material handling. In Sri Lanka, weighing instruments used for commercial transactions must be approved by the Measurement Units, Standards and Services Department (MUSSD) to ensure measurement accuracy, traceability, and public trust (Measurement Units, Standards and Services Department, 2024).

In recent years, cloud-enabled monitoring and data analytics platforms supplied by foreign vendors have been widely adopted to improve operational efficiency and transparency. Such industrial monitoring approaches have become increasingly common within modern IoT-enabled environments. However, many of these systems are incompatible with MUSSD-approved local weighing indicators. Conversely, several digitally advanced indicators that support modern communication interfaces are not legally approved for trade. This mismatch significantly restricts the lawful adoption of modern monitoring technologies within regulated weighing environments. The Hiweigh X1 is a widely deployed MUSSD-approved weighing indicator that provides industrial-grade accuracy and RS232 serial communication (Hiweigh Instruments, 2024).

Everest Instruments supplies monitoring systems commonly used in dairy collection networks for centralized data logging and operational dashboards. Direct integration between these systems is not feasible due to incompatible serial communication formats.

This paper presents a practical engineering solution in the form of an external data pattern conversion interface that preserves the legal integrity of the Hiweigh X1 while enabling interoperability with the Everest Instruments monitoring system. The solution avoids any modification to the weighing indicator and adheres strictly to established legal metrology practices.

<p>Mr. Rajitha Liyanage - B.Sc. (Electronic & Automation Technologies), HND (Electrical Engineering), AMIIESL; Engineering Researcher and Industrial Systems Developer, Sri Lanka.</p>

2.0 Literature & Regulatory Background

Legal metrology frameworks are established worldwide to protect consumers and traders by ensuring the accuracy and reliability of measurements used in commerce. In Sri Lanka, MUSSD regulates the approval, verification, and deployment of weighing instruments. Any modification that alters the metrological characteristics of an approved device may invalidate its legal status. Therefore, system integration solutions must remain external to the certified instrument.

From an engineering perspective, serial protocol conversion using microcontrollers is a well-established approach for integrating legacy industrial equipment with modern monitoring systems. RS232 communication remains common in weighing indicators, whereas contemporary microcontrollers operate using Transistor Logic (TTL) voltage levels. Devices such as the MAX3232 are widely used to provide safe and reliable RS232-to-TTL voltage level conversion (Maxim Integrated, 2025).

For modern monitoring applications, Internet of Things (IoT) communication paradigms emphasize low latency, reliability, and data freshness. Research has demonstrated the effectiveness of IoT-based monitoring systems in industrial environments (Al-Ali et al., 2024). Furthermore, the concept of Age of Information (Aoi) highlights the importance of minimizing the delay between data generation and data consumption in real-time monitoring applications (Sun, 2023). These principles influenced the firmware timing and buffering strategies adopted in the proposed protocol converter.

3.0 System Architecture and Hardware

A compact and scalable architecture was selected to enable easy deployment at existing installations. The system consisted of the following components:

- Hiweigh X1 weighing indicator with RS232 serial output (MUSSD approved)
- ESP32 microcontroller acting as the protocol converter.
- MAX3232 RS232–TTL level shifter for voltage adaptation and protection
- Everest Instruments monitoring unit with serial data input

The ESP32-based converter is installed in line between the weighing indicator and the monitoring unit. The Hiweigh X1 remains unchanged and continues to function as a legal metrology device. A regulated 5 V power supply, common grounding, and basic transient suppression components are used to ensure stable and reliable operation in industrial environments.

The overall system architecture and signal flow between the weighing indicator, protocol converter, and monitoring unit are illustrated in Figure 1.

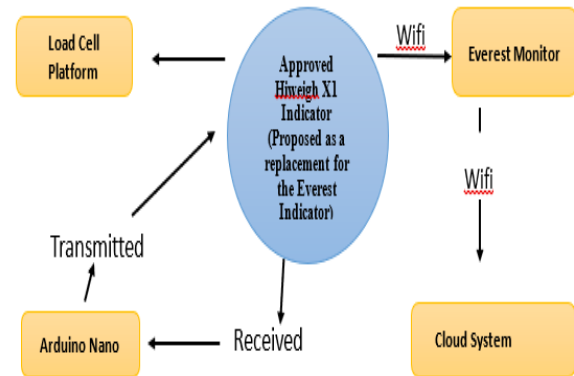


Figure 1: System Architecture

4.0 Protocol Analysis and Firmware Design

4.1 Native Frame Analysis

The Hiweigh X1 weighing indicator transmits measurement data through an RS232 serial interface using ASCII-encoded character frames. Each frame includes the numeric weight value, sign information, decimal placement, and status indicators such as measurement stability. These data elements are transmitted in a fixed sequence and terminated by predefined delimiter characters.

The Everest Instruments monitoring system expects incoming data in a different structured format, including specific header identifiers, field separators, and checksum values for data integrity verification. Due to this structural mismatch, direct communication between the two systems is not possible without intermediate data pattern conversion.

4.2 Data Pattern Conversion Methodology

The ESP32 microcontroller is programmed to function as a real-time protocol conversion interface. Incoming serial frames from the Hiweigh X1 are first validated to ensure correct length and structural integrity. The numeric weight value and associated status information are then extracted from the ASCII stream and temporarily stored in memory Figure 2.

Following extraction, the decoded data is reformatted into the exact data pattern required by the Everest monitoring system. This process includes reconstructing the data sequence, inserting required delimiters, and computing a checksum to ensure transmission integrity. The converted frame is then transmitted immediately to the monitoring unit, preserving both numerical accuracy and temporal relevance of the measurement data.

This approach enables seamless interoperability while ensuring that the original weighing indicator’s calibration, firmware, and legal metrology certification remain untouched.

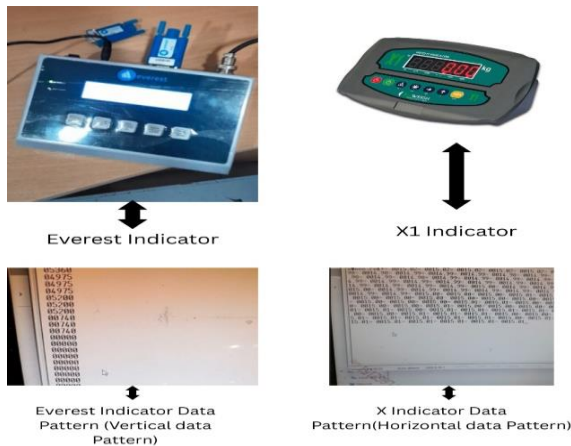


Figure 2-Sample Data Patterns Captured from Hiweigh X1 and Everest Indicators Using a Serial Monitor, Along with Images of the Indicators

4.3 Timing and Data Freshness Considerations

To maintain real-time responsiveness, validated data frames are forwarded immediately upon detection. During stable measurement conditions, periodic transmissions are maintained to confirm link continuity and system availability. This strategy minimizes latency while preventing unnecessary communication overhead.

5.0 Field Deployment & Test Procedure

The system is deployed at an operational dairy collection point where a Hiweigh X1 indicator is already in service. The protocol converter is connected inline without disturbing calibration seals or indicator settings. Continuous operation is maintained for 48 hours, capturing 1,000 weight readings under normal operational conditions, including varying loads and intermittent power interruptions. All readings are cross-verified against the indicator display.

6.0 Results

All 1,000 captured readings matched the Hiweigh X1 display values exactly, resulting in 0% numerical error throughout the evaluation period. The average end-to-end data transmission delay was measured to be below 200 ms, confirming near real-time performance suitable for operational monitoring. No packet corruption, repeated frames, or communication failures were observed during the continuous 48-hour deployment.

A representative subset of measurement results comparing the Hiweigh X1 indicator readings with the corresponding values received by the Everest monitoring system is presented in Table 1. The results demonstrate complete numerical consistency between the legally approved indicator and the converted monitoring output.

Table 1: Accuracy comparison between Hiweigh X1 indicator readings and converted Everest monitoring system values

Weight (kg)	X1 Reading (kg)	Everest Reading (kg)	Error
2.000	2.000	2.000	0.0
5.000	5.000	5.000	0.0
10.000	10.000	10.000	0.0
15.000	15.000	15.000	0.0
20.000	20.000	20.000	0.0

7.0 Discussion

The results demonstrate that an ESP32-based data pattern converter can successfully bridge a legally approved weighing indicator with a foreign monitoring platform without compromising regulatory compliance. The solution enables digital monitoring while preserving the integrity of the certified measurement chain.

The low cost, availability, and flexibility of the ESP32 make the approach suitable for large-scale deployment in dairy, retail, and industrial weighing applications. However, as the converter itself is not a legal metrology device, deployments intended for billing or settlement purposes should be implemented in consultation with MUSSD to ensure approved operational practices.

8.0 Conclusion

A practical and legally compliant data pattern conversion interface is designed and validated using an ESP32 microcontroller to integrate a MUSSD-approved Hiweigh X1 weighing indicator with an Everest Instruments monitoring system. The solution preserves numerical accuracy, achieves near real-time performance, and enables modern monitoring without modifying the weighing hardware. This work represents the first documented implementation of this specific integration in Sri Lanka and provides a scalable blueprint for future deployments.

9.0 Future Work

Future work may include extending the converter to support encrypted data transmission, secure cloud connectivity, and multi-indicator interoperability. Formal validation of such extensions under legal metrology regulations would further strengthen large-scale adoption.

10.0 Acknowledgements

The author gratefully acknowledges the technical support and test facilities provided by Averest Electro Systems (Pvt) Ltd and the guidance offered by officers of the Measurement Units, Standards and Services Department during regulatory clarification. Appreciation is also extended to the site staff for their cooperation during field trials

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Design and Risk Assessment of Fire Detection and Suppression Systems for Renewable Energy Installations: A Case Study on Solar PV and Battery Storage Applications

Best Article Section 1

Mr. H.K.R.H.J. Pamarathna

Abstract; The rapid integration of renewable energy technologies, particularly photovoltaic (PV) systems, battery energy storage systems (BESS), and wind power into modern power networks has introduced significant fire safety challenges. This research assesses fire risks across these technologies and proposes integrated strategies for detection, suppression, and prevention to improve operational resilience. Fire hazards in PV modules, BESS facilities, and wind turbines are identified and categorized, focusing on common initiating mechanisms and technical vulnerabilities. Case studies and incident reports are analyzed to determine recurring causes, failure patterns, and emergency response challenges. International fire safety frameworks and standards, including NFPA, IEC, and UL, are reviewed to benchmark best practices and identify limitations for renewable energy applications, particularly PV–BESS hybrid systems. Based on the hazard assessment and standards review, a fire safety model is developed for PV and battery storage applications, integrating early detection, effective suppression, and prevention-focused controls. The model is evaluated using Fire Dynamics Simulator (FDS) to simulate representative fire scenarios and assess mitigation effectiveness. The study also proposes practical fire safety guidelines tailored to tropical environments, accounting for elevated temperatures, humidity variation, and implementation constraints common in developing regions. The outcomes provide actionable recommendations to strengthen fire protection design and improve the safety and reliability of renewable energy installations.

Key Words: Renewable energy fire safety, Solar photovoltaic (PV), Battery energy storage systems (BESS), Fire detection and suppression, Fire Dynamics Simulator (FDS)

1.0 Introduction

1.1 Background

The global transition toward sustainable energy pathways has accelerated the deployment of renewable technologies including photovoltaic (PV) arrays, battery energy storage systems (BESS), and wind power infrastructure. These systems enable reductions in greenhouse gas emissions, improvements in energy security, and reduced dependence on fossil fuels. However, increased integration of renewables has intensified concerns around safety challenges; particularly fire hazards; because these systems combine electrical complexity, high-energy-density equipment, and exposure to demanding environmental conditions. (Wu et al., 2020)

Fire safety in renewable energy applications has become a major research focus following notable incidents linked to PV modules and lithium-ion BESS facilities internationally. Such incidents have led to property damage, risks to human life, and in some cases disruptions that affect operational continuity and grid stability (Cabrera-Tobar et al., 2025). Despite rapid renewable energy deployment, fire

safety frameworks have often struggled to keep pace with technological change, creating gaps in hazard identification, standards coverage, and system resilience. These challenges are more pronounced in tropical and developing regions, where localized regulations and climate-adapted engineering guidance are limited.

Although PV systems are commonly viewed as passive due to the absence of moving parts, they still present fire risks associated with substandard installation practices, defective components (such as connectors and inverters), and inadequate maintenance. Typical initiating events include arcing faults, ground faults, and localized overheating.

These risks become more critical in rooftop PV installations because a fire can threaten building integrity and complicate suppression and emergency response. (Wu et al., 2020; Hu et al., 2013; Hu et al., 2014)

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BESS installations; often coupled with PV to address intermittency and improve resilience; introduce even more complex fire hazards. Lithium-ion technologies can experience thermal runaway, a self-propagating reaction that is difficult to stop once initiated and may spread across adjacent cells, leading to severe fires or explosions. International incident experience highlights the need for improved detection, containment, and suppression strategies designed specifically for energy storage environments (Al Wahedi & Bicer, 2024; Larsson et al., 2017). Wind energy systems are less frequently associated with fire events, but fires can occur due to electrical faults, overheating, or lightning strikes within turbine nacelles. While probability may be lower compared to PV and BESS, consequences can be severe due to access limitations and remote locations.

Given these challenges, this research focuses on developing robust, context-specific fire safety approaches for renewable energy installations. Conventional detection and suppression methods are unreliable in outdoor PV settings or unsuitable for electrical fires and battery enclosures (Fang et al., 2019). Therefore, advanced modelling tools such as Fire Dynamics Simulator (FDS) are used to predict fire behavior and evaluate mitigation methods. The study further acknowledges that global standards (NFPA, IEC, UL) are evolving but may lack specificity for tropical environments where high temperature, humidity, and long-term environmental stress affect reliability and risk (Sirisak et al., 2022).

1.2 Problem Statement

Despite global renewable energy expansion, a critical gap remains in ensuring adequate fire safety across PV and BESS infrastructures. Existing frameworks are frequently inadequate for tropical contexts where climatic conditions increase the likelihood of faults and reduce the effectiveness of generic detection / suppression approaches. Conventional systems may underperform due to outdoor exposure, compact equipment housings, and electrical incompatibility.

As a result, renewable energy projects remain vulnerable to catastrophic fire incidents that can compromise infrastructure reliability, threaten human safety and reduce confidence in sustainable technologies. Without tailored fire protection strategies, risks of property damage, operational disruption, and reputational harm persist. This research addresses this gap by investigating integrated and simulation-driven strategies for fire detection and suppression, adapted specifically to PV and BESS systems in tropical regions.

1.3 Aim

The broad aim of this work is to evaluate fire risks in renewable energy systems and develop effective fire detection and suppression strategies for enhanced safety and system resilience.

1.4 Objectives

This research has the following objectives:

- Identify and classify fire hazards in PV, BESS and wind systems to establish a structured baseline for comparing risks across technologies.
- Analyze real-world fire incidents and root causes to link theoretical hazards with observed failures and identify recurring patterns.
- Review and evaluate international fire protection standards (NFPA, UL, IEC, ISO) and assess applicability to tropical environments.
- Design an optimized fire safety model for PV/BESS, integrating early detection, suppression, and isolation strategies.
- Simulate fire risk scenarios using FDS to validate assumptions and quantify mitigation effectiveness.
- Propose fire safety guidelines tailored to tropical climates to deliver actionable recommendations for practitioners and policymakers.

1.5 Scope of the Project

Inclusions:

- Hazard identification and classification
- Standards review
- Case study analysis
- Fire safety model design
- Computational simulation using FDS for PV applications

Exclusions:

- Full-scale prototyping
- Long-term operational monitoring

Boundaries:

- Focus on tropical climatic conditions (e.g., Sri Lanka / South Asia), where environmental stresses increase fire risks and demand climate-adapted guidance.

2.0 Literature Review

2.1 Fire risk context in renewable energy systems

Rapid global adoption of renewable energy technologies has expanded the fire-risk landscape, particularly for photovoltaic (PV) systems and battery energy storage systems (BESS). PV fire risk is strongly linked to ageing, environmental exposure, and electrical faults, while BESS adds chemical and thermal hazards that can escalate quickly when abnormal conditions occur (Wu et al., 2020; Cabrera-Tobar et al., 2025).

In tropical environments, elevated temperature and humidity accelerate insulation deterioration, promote corrosion, and reduce cooling effectiveness, increasing the probability that faults progress into sustained fire events (Sirisak et al., 2022). The major contributing factors associated with PV module fire incidents are illustrated in Figure 1.

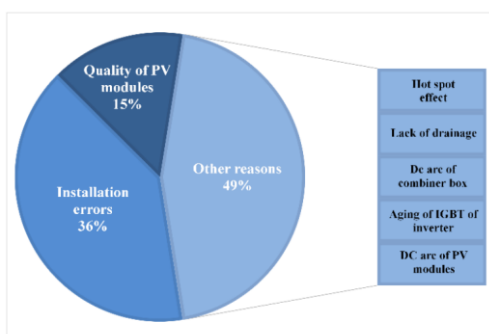


Figure 1: Factors leading to PV module fire accidents. (Wu et al., 2020)

Hot spot effects are identified as another critical PV hazard. They occur due to non-uniform current distribution, frequently caused by partial shading or surface soiling, creating localized overheating conditions that can accelerate degradation and increase ignition likelihood (Wu et al., 2020).

2.2 Detection and suppression challenges for PV and hybrid PV-BESS

PV and hybrid PV-BESS installations require fire protection strategies that account for electrical hazards and system interdependencies. Conventional approaches may not sufficiently address advanced arc fault detection and real-time suppression integration, even where PV module construction and installation protocols are covered by standards such as IEC 61730 and IEC 62446 (IEC, 2021).

Suppression technologies are evolving toward solutions better suited to electrical and enclosed energy hazards, including aerosol-based extinguishers and pre-chamber gas suppression units for battery racks. In contrast, water-based sprinklers may be ineffective or counterproductive in some electrical fire scenarios (Fang et al., 2019).

2.3 Standards-based safety governance for PV-BESS

Hybrid PV-BESS installations combine electrical, chemical, and thermal hazards and therefore require a structured governance framework. Internationally recognized standards and test methodologies; including NFPA 855, the IEC 62933 series, and UL 9540A; form the core reference structure for safe design and operation of modern energy storage installations.

These frameworks establish layered defenses: prevention through design, early detection and protective control functions, and containment through installation requirements and validated mitigation performance. Tropical climates introduce accelerated component ageing and more demanding ventilation and thermal management requirements, supporting the need for context-specific adoption of globally developed standards.

NFPA 855: installation requirements for stationary energy storage systems

NFPA 855 defines key installation constraints for stationary ESS, including ventilation provisions to prevent explosive gas accumulation and thermal management to maintain safe operating temperatures and reduce thermal runaway susceptibility. Ventilation rates can be derived from UL 9540A gas analysis, linking installation design to measured fault behavior.

NFPA 855 also addresses detection and suppression coordination, supporting listed detection systems and suppression options such as clean agents, water-based systems where applicable, and aerosols for cabinets. Selection depends on fire test data, chemical compatibility, and applicable local fire codes, with more detailed coordination guidance introduced in updated editions.

Although NFPA 855 does not explicitly target tropical climate effects, its requirements for thermal management, ventilation, and fire separation remain directly relevant. Increased ventilation capacity, humidity-controlled enclosures, and enhanced corrosion protection are practical climate adaptations, where high humidity and temperature increase hazard likelihood.

IEC 62933: environmental guidance and verification for electrochemical storage

The IEC 62933 series, provides a performance-oriented framework that complements prescriptive installation codes by defining environmental guidance, unit parameters, and testing methods for energy storage systems (IEC, 2017a; IEC, 2017b).

IEC TS 62933-4-1 emphasizes the interface between product capability and ambient stressors such as temperature, humidity, and contamination. These factors influence safety and longevity, supporting mitigation by design through enclosure choices, IP ratings, HVAC/dehumidification, and protective coatings; particularly relevant for PV-BESS deployments in tropical climates (IEC, 2017a).

UL 9540A: thermal runaway propagation and mitigation validation

UL 9540A provides a basis for evaluating thermal runaway behavior and propagation at multiple levels (module, unit, installation), informing containment, spacing, ventilation, and suppression decisions.

Key metrics include temperature, heat release rate (HRR), gas composition (including hydrogen, carbon monoxide, methane, and toxic fluorinated compounds), gas volume and venting duration, flame spread time, and suppression effectiveness under realistic conditions.

Test evidence emphasizes that gas release can peak before visible flames, supporting early gas detection. Installation-scale evidence indicates that spacing and non-combustible barriers reduce propagation probability, and that clean agents and aerosols perform best when applied prior to open-flame development; delayed activation reduces containment success.

For tropical PV–BESS applications, UL 9540A data supports derating and thermal stress reduction, corrosion-resistant venting for acidic gases, redundant multi-sensor detection (thermal, gas, arc-fault), and suppression triggers tuned to gas evolution rather than temperature alone (UL, 2019; UL, 2020; UL, 2021).

2.4 Integrated risk assessment framework for PV–BESS in tropical environments

A combined governance structure that connects NFPA 855 (installation constraints), IEC 62933 (environmental and verification requirements), and UL 9540A (validated failure behavior) supports a policy–performance–proof chain for PV–BESS fire safety.

This integrated set can be embedded into structured methods such as FMEA (Failure Mode and Effects Analysis), FTA/ETA (Fault Tree Analysis / Event Tree Analysis), and STPA (Systems-Theoretic Process Analysis): NFPA 855 supports failure identification and safety constraints, IEC 62933 informs environmental stress adjustments and control setpoints, and UL 9540A provides quantified severity, propagation behavior, and suppression effectiveness for evidence-based risk scoring.

Tropical adaptation strengthens the framework by incorporating IEC-derived derating, increasing ventilation/spacing margins to offset reduced cooling efficiency, and moving suppression triggers earlier using UL 9540A gas-evolution indicators.

2.5 Wind turbine safety standards and practices

Wind turbine systems also face fire hazards, including nacelle fires driven by electrical short circuits, bearing overheating, and lightning. These are recognized contributors to wind insurance losses (Tavner et al., 2020).

A layered compliance approach is supported through NFPA 850, NFPA 70, UL 6141, UL 6142, and the IEC 61400 series, integrating fire protection design, electrical system integrity, and lifecycle design and operational safety requirements. Tropical environments heighten risks through humidity, salt corrosion, and frequent lightning exposure, increasing the value of enhanced lightning protection and robust grounding and bonding practices.

3.0 Methodology

A mixed-methods methodology is used to evaluate fire risks in photovoltaic (PV) and battery energy storage systems (BESS), combining qualitative and quantitative techniques to integrate operational insights with technical risk modelling (Creswell and Plano Clark, 2018). This approach addresses the multi-factor nature of renewable-energy fire hazards and supports robust recommendations by capturing both probabilistic behavior and practical constraints (Wu et al., 2020; Cabrera-Tobar et al., 2025).

A case study approach supports contextual analysis using site-specific technical, regulatory, and environmental data, with reliability enhanced through methodological triangulation (Yin, 2018; ISO 31010, 2019). Risk assessment applies FMEA, HAZOP, FTA, ETA, and STPA, supported by FDS/Smoke view simulations to evaluate fire development and mitigation performance (Creswell & Plano Clark, 2018; NIST, 2023).

3.1 Fire Dynamics Simulator (FDS) Model Setup

Fire Dynamics Simulator (FDS Version 6.9.1, NIST) was used to evaluate fire development and suppression effectiveness within a representative rooftop PV installation. The model simulated an ignition event beneath a PV module, representing electrical faults such as connector overheating or DC arcing. A section of a rooftop PV array was modelled to assess fire growth, heat release, smoke propagation, and temperature distribution under tropical operating conditions. Smoke view was used to visualize fire and smoke behavior, while simulation outputs including Heat Release Rate (HRR), radiative heat flux, and smoke movement

were analyzed to evaluate the effectiveness of detection and suppression measures. The principal FDS model assumptions and simulation parameters are summarized in Table 1.

Table 1: Input Parameters

Parameter	Value	Reference
Domain size	3.0 × 3.0 × 1.5 m	Simulation design
Mesh size	0.05 m	FDS guidance
Fire source	0.20 × 0.20 m patch	Prescribed
HRRPUA	2500 kW/m ²	Literature baseline (Fang et al., 2019)
Radiative fraction	0.35	NFPA 92, McGrattan et al.

The selected parameters represent a conservative electrical-fault ignition scenario intended to evaluate fire growth and mitigation effectiveness under tropical rooftop operating conditions.

4.0 Case Study – Rooftop Solar PV Installation (6.9 MW)

This chapter presents a real rooftop PV project as the empirical basis to evaluate fire hazards and validate the proposed methodology using site evidence and risk-analysis tools. The case is suitable because it represents a large-scale rooftop deployment operating in a tropical environment, where heat, humidity, and exposure conditions can influence electrical degradation and increase ignition likelihood.

4.1 Project Background

The case study is a 6.9 MW rooftop PV installation commissioned on 31 August 2023, consisting of 11,609 modules distributed across multiple factory rooftops, with AC export aligned to CEB interconnection requirements. The installation is exposed to high irradiance, elevated rooftop temperatures, and humidity conditions that can accelerate insulation breakdown, connector wear, and hot-spot formation, and therefore require risk evaluation at both component and system levels. An aerial view of the installation used for the case study is presented in Figure 2.



Figure 2: Aerial site view of rooftop installation (EGFI, 2023)

A preliminary ISO 31010-style risk matrix is used to classify hazards and frame the deeper assessment. Identified dominant hazards include DC arc faults in rooftop string cabling, hot-spot formation due to shading, and isolator mechanical failure, supporting the focus on electrical fault ignition pathways in rooftop PV. The operational fire monitor arrangement evaluated during site inspections is shown in Figure 3.

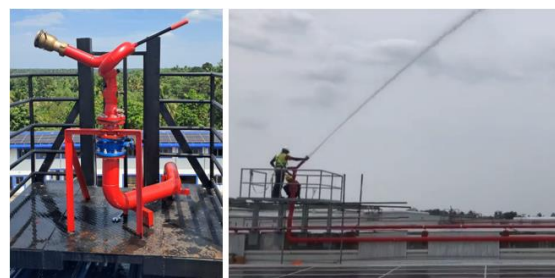


Figure 3: Operational Test – Fire Monitor in Action

Site inspections confirmed the installation of fire water monitors and open sprinkler systems across the rooftop PV area. Monitors were strategically positioned to provide effective coverage of PV module strings, while open sprinklers were connected to the fire hydrant system for continuous discharge. Commissioning tests demonstrated adequate water throw and coverage. Figure 4 illustrates the operational testing of the rooftop open-sprinkler system.



Figure 4: Operational test - Open Sprinkler Line in Action

The case study is positioned as the central validation platform to: apply structured tools (FMEA/FTA/STPA), evaluate fire detection in an operational PV setting, benchmark suppression readiness against relevant guidance, and validate outcomes using interviews and inspection evidence.

4.2 Comprehensive Risk Assessment

The risk assessment is designed to identify, evaluate, and mitigate fire hazards in line with ISO 31010:2019, combining qualitative inputs (site inspections, interviews, log reviews, compliance audits) and quantitative tools (FMEA/FTA/ETA).

A component-focused FMEA ranks major failure modes. The highest RPN identified is related to MC4 connector heating (RPN 288), making connector workmanship/ moisture ingress/ thermal scanning priorities. Cable insulation degradation is also highlighted as a high-likelihood/ high-severity hazard due to outdoor exposure, and maintenance intervals are flagged for adjustment under tropical conditions.

Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) were applied to model rooftop PV fire initiation and escalation pathways. Key ignition contributors are DC arc faults driven by cable insulation breakdown and connector failure, hot-spot escalation associated with bypass diode failure, and inverter-side DC input failure, which together define the dominant causal routes to module ignition and rooftop fire development. The escalation pathway is governed by barrier performance: AFCI - based (Assessment of arc fault circuit interrupters) detection, rapid DC isolation via disconnects, and suppression through portable extinguishers and external firefighting response, producing outcomes ranging from contained incidents to rooftop-wide fire spread. Probability-weighted evaluation indicates that effective coupling of early detection and rapid DC isolation reduces potential fire damage by over 80%.

5.0 Case Study Description – BESS Installation

The case study examines the battery energy storage installation at the Watch Tower Bible and Tract Society facility in Sri Lanka, selected as a representative solar-plus-storage implementation under tropical operating conditions. The system integrates rooftop solar PV with Huawei’s LUNA2000-2.0MWH-2H1 Battery Energy Storage System (BESS) and is used to evaluate system-level fire-risk controls and mitigation readiness (Huawei Technologies Co., Ltd., 2021).

The 2.032 MWh LUNA2000 BESS is installed in a dedicated service yard near PV inverters to reduce losses and ensure safe access, featuring LFP chemistry, IP55 enclosure, and smart cooling for tropical conditions (Hayleys Solar, n.d.; Huawei Technologies Co., Ltd., n.d.; 2021).

Fire safety is implemented as layered protection: internal sensing (temperature and smoke/gas monitoring), integrated clean-agent suppression (FM-200 / Novec 1230™), and automatic isolation functions intended to limit escalation within the container. Facility-level provisions include dedicated extinguishers and defined clearance for

response access, integrated with site monitoring arrangements.

Preventive maintenance is conducted quarterly, including checks on cooling performance, suppression cylinder pressure, and system diagnostics, with minor operational alarms addressed through O&M actions without recorded major thermal events.

6.0 Discussion

This chapter consolidates findings from FDS simulations, expert interviews, and site inspections to interpret fire-risk behavior in rooftop PV and BESS installations and to evaluate the effectiveness of detection and suppression strategies under tropical conditions. FDS outputs indicate that a small ignition source beneath a PV module can generate radiative heat flux exceeding 15 kW/m² at the underside surfaces, which is sufficient to initiate ignition of polymer-based PV materials; this aligns with reported PV material susceptibility under high radiant flux exposure (Wu et al., 2020; Fang et al., 2019).

Smoke visualization indicates recirculation and stagnation beneath panel standoff spaces, which can delay response if relying only on point smoke detection. Practical recommendations provided through interviews support enhanced detection approaches (e.g., linear heat detection or video-based detection) to address semi-enclosed rooftop microenvironments. Representative Smokeview outputs showing plume development at different simulation times are presented in Figure 5.

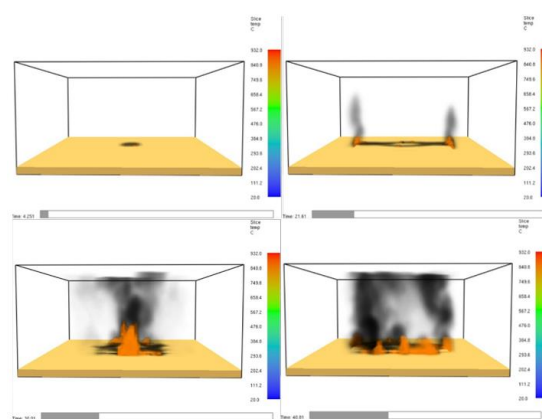


Figure 5: 3D Smokeview plume @ 4, 20, 30 & 40s

Fire spread modelling indicates that without active suppression, PV fire can propagate to an adjacent module in approximately 8–12 minutes under tropical wind conditions. Active roof suppression (sprinklers/monitors) limits growth, confines the damage to a localized area (single-module scale), and caps heat release rate (HRR) to <150 kW, demonstrating the value of early suppression

where conditions allow effective water delivery. Outdoor application limitations remain significant because wind drift can reduce coverage and increase demand for redundancy and frequent maintenance, especially in humid tropical environments prone to corrosion and scaling.

Barrier-based interpretation reinforces that suppression cannot be treated as a standalone safeguard. Effective performance depends on electrical isolation (e.g., rapid shutdown/AFCI and disconnect coordination), reflecting the standards emphasis on isolation and integrated fire protection requirements (NFPA, 2023).

For the BESS case, modelling of thermal runaway behavior indicates that LFP chemistry has higher ignition thresholds (noted as $>250^{\circ}\text{C}$ compared to NMC), and rack-level isolation reduces propagation probability. Clean-agent suppression modelling (FM-200/Novac 1230) indicates rapid effectiveness (<30 seconds after detection) and containment within a single rack, while preserving equipment integrity compared to water-based suppression.

7.0 Conclusions

This research evaluated fire risks in renewable energy installations with emphasis on rooftop photovoltaic (PV) systems and battery energy storage systems (BESS). By combining literature-based hazard identification, case study evidence, simulation outputs, expert inputs, and site observations, the work developed an integrated view of ignition pathways, fire development, detection limitations, and suppression effectiveness under tropical operating conditions.

For the 6.9 MW rooftop PV installation, the findings confirm that dominant ignition pathways are associated with DC-side electrical failures, including connector/ cable arc faults and hot-spot formation linked to shading effects and protection-device degradation (Wu et al., 2020). Simulation outputs indicate that even small ignition sources beneath PV modules can generate radiative heat flux levels ($>15 \text{ kW/m}^2$) sufficient to accelerate back-sheet polymer deterioration and initiate ignition, aligning with known PV material susceptibility under high radiant loading (Wu et al., 2020; Fang et al., 2019). Practical assessment further indicates that smoke movement and recirculation beneath panel stand-offs can delay activation of conventional detectors, supporting the need for linear heat detection and/or intelligent visual detection in rooftop PV layouts. Importantly, the evaluated suppression approach, open sprinklers and rooftop monitors combined with rapid DC isolation is effective for limiting fire growth and sectional spread, with sprinklers also functioning as a compartmentation mechanism across rooftop zones.

For the BESS case context (Huawei LUNA2000), the study highlights the value of layered controls: selection of Lithium Iron Phosphate (LFP) chemistry and the integration of clean-agent suppression (FM-200/Novac 1230) and smart monitoring to reduce escalation potential and reliance on manual intervention. Finally, across PV and BESS, evidence consistently indicates that early detection and rapid isolation are more decisive for risk reduction than suppression alone, particularly where heat, humidity, and wind reduce system reliability and suppression effectiveness in tropical environments.

7.1 Further Work

Future studies should expand simulation to array-scale fire spread with wind coupling; conduct material-specific fire testing for locally used PV encapsulants/back-sheets to improve model inputs; empirically evaluate suppression performance under tropical wind and rainfall; and pursue long-term BESS reliability studies including monitoring effectiveness. In addition, integrating predictive maintenance and anomaly detection into PV-BESS operations can strengthen prevention and reduce fault-to-fire progression.

Acknowledgement

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Development of an Automatic Wheel Alignment Detection System

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Abstract; Accurate wheel alignment is essential for vehicle safety, optimal handling, reduced tire wear, and improved fuel efficiency. Traditional wheel alignment checks are manual, time-consuming, and often neglected by vehicle owners until significant symptoms arise. This paper presents the design and development of an automatic wheel alignment detection prototype aimed at providing real-time angle measurements for a vehicle's camber and toe configurations. The primary objective is to build a low-cost, continuous monitoring framework that detects deviations within an accuracy of $\pm 0.5^\circ$. The proposed system comprises an inertial sensor module, a potentiometer-based steering tracking unit, a microcontroller-based processing core, and a real-time data monitoring display. A functional prototype was implemented using an MPU6050 IMU sensor, a rotary potentiometer, and an Arduino Nano microcontroller coupled with an LCD unit for local data visualization. Experimental validation demonstrates that the system accurately identifies dynamic misalignments under distinct steering positions (zero-position, maximum left, and maximum right) while substantially reducing inspection complexity.

Keywords: wheel alignment, real-time monitoring, sensor integration, camber, toe angle.

1.0 Introduction

Automobile efficiency and vehicle dynamics remain focal areas of modern transport engineering. While manufacturers deploy state-of-the-art chassis systems to fulfil safety norms and stringent carbon emission regulations, secondary operational parameters like wheel alignment are historically overlooked by standard vehicle owners. Misaligned geometry introduces high rolling resistance, accelerated mechanical degradation, and unpredictable handling characteristics that jeopardize passenger safety.

Out-of-specification camber causes asymmetrical tire tread wear, inducing lateral pulling forces toward the side with higher positive camber during straight-line tracking. Conversely, incorrect toe settings force tires into a continuous scrubbing action against the road surface. This increased rolling resistance leads to rapid, premature tire wear on both sides and alters the vehicle's thrust angle. Consequently, the steering wheel shifts away from the true center during linear travel, degrading steering predictability.

Unchecked primary alignment angles diminish overall automotive efficiency by demanding greater fuel expenditure to overcome road friction. Furthermore, suspension linkages undergo uneven force distributions, requiring premature mechanical replacements. This lifecycle degradation causes

indirect environmental damage; manufacturing replacement components elevates carbon footprints through industrial energy consumption. Despite these critical implications, low-cost frameworks for continuous, onboard alignment telemetry remain underrepresented in literature.

Main wheel alignment terms,

- Camber
- Caster
- Toe
- Steering Center

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To resolve the high economic barrier and diagnostic delays of commercial alignment rigs, the primary objective of this study is to design, implement, and validate a low-cost, embedded sensor prototype for automated, real-time wheel alignment monitoring. The targeted scope of this work is explicitly defined as follows,

- Development of a localized hardware system optimized for small-scale automotive workshops and onboard telematics.
- Dynamic tracking restricted to two primary alignment criteria: Camber Angle (via tilt telemetry) and Toe Angle (correlated against steering position).
- Experimental verification bounded by three static steering boundaries: Zero-position (0°), Maximum Left (approx -63°), and Maximum Right (approx $+63^{\circ}$).
- *Exclusion Boundary:* Caster angle determination is excluded from this iteration due to the spatial constraints of single-axis IMU displacement during cross-axis steering turns.

2.0 Literature Review

2.1 Measurement of Wheels Alignment using IR Sensor

To contextualize embedded sensing within automotive diagnostics, multiple industrial methodologies must be analyzed. Mechanized wheel tracking has progressed from optical tracking arrays to complex machine vision pipelines.

Prior research highlights diverse approaches to parameter acquisition. Barhe and Gawalwad explored an infrared (IR) sensor array mounted directly near the wheel hub assemblies, feeding a signal conditioning block to map angular variances on an ATmega328P platform (Figure 1). While cost-effective, IR arrays are highly susceptible to ambient light interference and mud scatter in rugged field environments. To mitigate line-of-sight constraints, Li et al. and Wang & Tu developed robust computer vision configurations using high-definition cameras to track planar target boards attached to the wheels. These vision-based systems provide precise multi-parameter tracking but demand massive projective geometrical calculation loops and costly imaging hardware, making them unsuitable for budget-conscious applications.

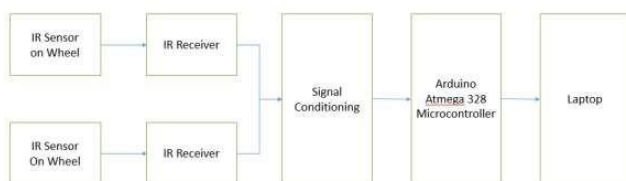


Figure No 01: IR sensor-based system flow chart

2.2 Wheel Alignment Inspection by 3D Point Cloud Monitoring

Alternative low-cost vision variants try to simplify calculations. Beak, Cho, and Bang proposed a 3D point cloud monitoring pipeline using a Microsoft Kinect depth sensor as an alternative to expensive CCD setups. By processing spatial surfaces directly from point clouds, their prototype eliminated the need for complex target calibrations and proved commercial feasibility on single-wheel testbeds. However, point cloud rendering remains computationally heavy for real-time onboard microcontrollers.

Beyond image processing, foundational wheel kinematics models developed by Furukawa et al. and measurement techniques by Díaz et al. confirm that geometric tracking must account for dynamic steering angles to avoid false misalignment flags. Furthermore, mechanical adjustment mechanisms outlined in industrial patents by Healy, Jackson, and January confirm that tracking transient variations in camber and toe under distinct steering vectors provides deep prognostic value. This research fills that gap by integrating a solid-state Micro-Electro-Mechanical System (MEMS) IMU with a linear potentiometer to establish a lightweight, direct-measurement model that skips both heavy optical environments and complex spatial calculation loops.

3.0 Methodology

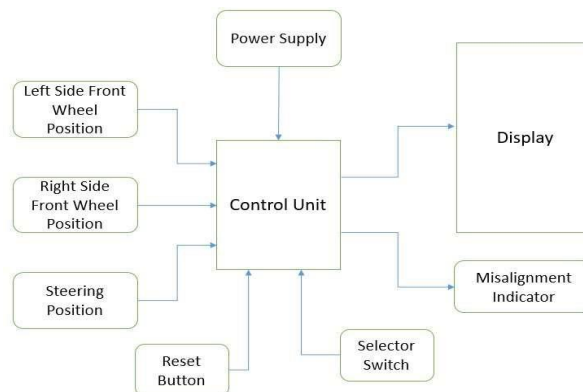


Figure 02: Control system structure

The automatic detection architecture is organized into four distinct functional domains: Sensors, Control Processing, Power Delivery, and Misalignment Indication (Figure 2).

To minimize physical stress from linear acceleration, sensor edge nodes are mounted securely near the wheel center caps. The central control unit is located in the cabin to protect it from road vibrations and ensure access to a stable power supply.

3.1 Control System

All operations of the sensor are controlled by a single microcontroller (Arduino Nano) that tells the sensors and the transceiver when to read or write data. Since the system is mostly in an idle state the microcontroller is not executing code and is in a no-op loop until it receives an outside command from the central node. The microcontroller then targets the sensors to turn on the sensors for the sampling period until the data collection is complete. After the collecting data, if misalignment is identified from front wheels, different angles can be identified easily.

3.1.1 Microcontroller (Arduino Nano Board)

Arduino Nano is a microcontroller board designed by Arduino.cc. The microcontroller used in the Arduino Nano is Atmega328, the same one as used in Arduino UNO. It has a wide range of applications and is a major microcontroller board because of its small size and flexibility.

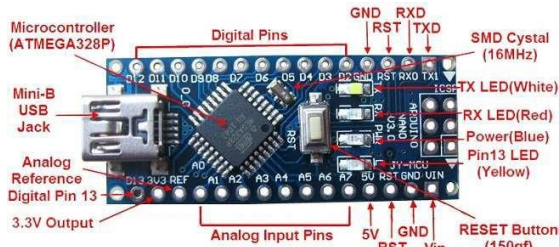


Figure No 03: Arduino nano Microcontroller

3.1.2 Sensor System

The device that used for the gathering of acceleration data for calculating angle data was the MPU6050 accelerometer. This device has a resolution of 16383 LSB/g this resolution allows for the precision of the device to be accurate to 0.1°. The device has support for I2C it has a simple communication protocol that allows for an easy interface with the microcontroller. The device's power characteristics allow the device to be in an idle, "powered down", state that uses minimal current. This allows the node to consume minimal power when it is in a wait state. The noise density that affects the calculations is insignificant after 20 samples. This allows the calculations to be performed without additional hardware.

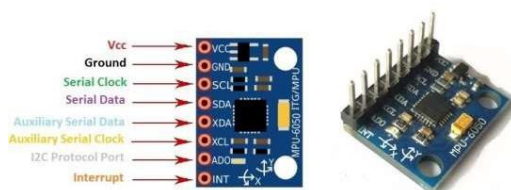


Figure 04: Architecture of MPU 6050

3.1.3 Software

The software of the device needed to be a real-time system, such that every task was an aperiodic scheduled task with priority. Taking the measurements had the highest priority, however a command from the central node to stop measuring could act as a SIGKILL which would override the task. However, in general the system has linear behavior that can act as a periodic system, albeit the system would not optimize CPU time unless the calculations could schedule in between the sampling periods.

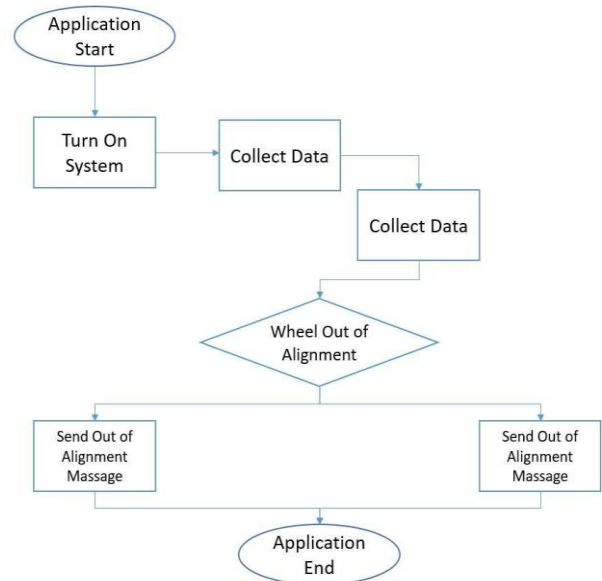


Figure 05: System Flow chat

4.0 Implementation, Testing & Results

The implementation of the system included the power system, control system, sensors, and output devices. The power system was verified by connecting a test probe to the output terminal to ensure that the supply voltage remained within ±5% of the nominal 5 V value. The control system verification involved testing the Arduino Nano microcontroller to confirm its ability to communicate with the connected modules and perform the calculations required for the basic operation of the project, including receiving correct identifier responses from the sensors. The sensor unit measured data from the accelerometer to determine the camber and toe angles, while an additional potentiometer signal was used to verify the position of the steering wheel. The output devices, including the display, indicators, and speakers, were used to indicate front wheel misalignment; when the difference in toe or camber angle exceeded 5°, an alarm was activated and the angle difference was displayed.

4.1 Testing & Result

Table 01 presents the testing values obtained when the steering wheel was maintained at zero position. The results show different combinations of camber and toe angles and their corresponding differences from the reference values. When both the camber and toe angle differences remained within the acceptable limit of 5°, the alarm status remained off, and the wheel alignment condition was identified as good. However, when the toe angle difference exceeded the threshold, the alarm was activated, indicating misalignment in toe. Similarly, excessive camber angle differences resulted in a camber misalignment indication. In cases where both chamber and toe angle differences exceeded the permissible range, the system correctly identified misalignment in both toe and camber and activated the alarm accordingly.

Table 01: Testing values for Steering zero position

Steering Position	Camber Angle	Toe Angle	Reference of both Different	Camber Angle Different	Toe Angle Different	Alarm Status	Wheel Alignment Status
0.18°	-19.93° -21.41°	5.65° 6.08°	0.00	-1.48°	0.43°	off	Good
0.25°	-20.02° -21.36°	10.63° 4.25°	0.00	-1.34°	6.38°	on	Misalignment in Toe
0.16°	-22.56° -17.25°	5.54° 6.12°	0.00	-5.31°	0.58°	on	Misalignment in Camber
0.20°	-22.31° -16.58°	10.36° 5.15°	0.00	-5.73°	5.21°	on	Misalignment in Toe and Camber

Table 02 illustrates the test results obtained when the steering wheel was rotated to the maximum left position. The steering angle values were approximately -63°, and corresponding camber and toe angles were measured. When the camber and toe angle differences were within the acceptable range, the alarm remained off and the wheel alignment status was indicated as good. An increase in toe angle difference beyond the threshold caused the alarm to turn on, indicating toe misalignment. Similarly, excessive camber angle differences resulted in camber misalignment detection. When both camber and toe angle differences exceeded the limit, the system successfully identified misalignment in both parameters and activated the alarm.

Table 02: Testing values for Steering wheel left side maximum

Steering Position	Camber Angle	Toe Angle	Reference of both Different	Camber Angle Different	Toe Angle Different	Alarm Status	Wheel Alignment Status
-63.18	-19.87 -21.23	63.46 63.86	0.00	-1.36	0.4	off	Good
-63.56	-20.43 -21.36	63.51 58.21	0.00	-0.93	5.30	on	Misalignment in Toe
-63.93	-20.58 -26.25	63.38 63.72	0.00	-5.67	0.34	on	Misalignment in Camber
-62.95	-20.62 -26.35	63.21 57.25	0.00	-5.73	5.96	on	Misalignment in Toe and Camber

The test results for the steering wheel rotated to the maximum right position are shown in Table 03. The steering angle values were approximately +63°, with corresponding camber and toe angle measurements recorded. When both camber and toe angle differences were within ±5°, the alarm status remained off and the wheel alignment was considered satisfactory. If the toe angle difference exceeded the allowable range, the system detected toe misalignment and activated the alarm. Excessive camber angle differences triggered camber misalignment detection, while combined deviations in both camber and toe angles resulted in the alarm indicating misalignment in both parameters. These results confirm the system's ability to accurately detect wheel misalignment under right-side steering conditions.

Table 03: Testing values for Steering wheel right side maximum

Steering Position	Camber Angle	Toe Angle	Reference of both Different	Camber Angle Different	Toe Angle Different	Alarm Status	Wheel Alignment Status
63.67°	-19.03° -21.69°	-65.58° -64.32°	0.00°	-2.66°	-1.26°	off	Good
63.21°	-19.67° -21.18°	-65.02° -57.25°	0.00°	-1.51°	-7.77°	on	Misalignment in Toe
63.85°	-20.86° -26.01°	-64.25° -64.85°	0.00°	-5.15°	-0.06°	on	Misalignment in Camber
62.74°	-20.55° -25.99°	-64.80° -59.31°	0.00°	-5.44°	5.49°	on	Misalignment in Toe and Camber

5.0 Discussion

The empirical measurements verified across Tables 1, 2, and 3 demonstrate that the system successfully tracks geometric variations by cross-referencing spatial accelerometer tilt arrays against potentiometer steering voltage states. When the calibrated structural limits remained within the permissible window (< 5.0°), the automated logic suppressed alarms and logged a "Good" operational status. Conversely, when threshold bounds were breached, the system isolated individual axis faults to flag explicit "Toe" or "Camber" errors.

To deploy this embedded device within a functional automobile passenger cabin, a secondary mechanical speed-reduction gearbox assembly must be paired with the vehicle's steering column. This gear coupling matches the multi-turn rotation of a standard steering rack to the electrical range of a standard precision potentiometer, preventing sensor saturation and ensuring accurate steering angle tracking.

6.0 Conclusions

This study presents the design, implementation, and verification of a low-cost, real-time wheel alignment monitoring prototype utilizing MEMS telemetry. By employing an embedded algorithmic framework, the device tracks Camber variations and correlates Toe deviations against physical steering adjustments. Across all testing scenarios including zero position tracking and maximum steering locks the prototype successfully logged structural errors whenever deviations exceeded the 5⁰-boundary limit. The system provides clear, localized visual alerts without requiring heavy optical equipment or complex external computation loops.

Future work will expand the onboard code to track high-frequency dynamic noise filters, transforming the hardware from a workshop testing unit into a continuous tracking module for commercial transport vehicles.

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Design and Implementation of a Force main Sewer Connection System for an Urban Healthcare Facility: Ayurveda National Hospital Project, Colombo 08

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Abstract: Urban hospitals generate wastewater under continuously varying flow conditions, requiring reliable and efficient conveyance systems to ensure safe disposal and environmental protection. This paper presents a **case study** of the design and planned implementation of a force main sewer connection system for the Ayurveda National Hospital, Colombo 08, developed under the urban sewerage improvement programme of the Colombo Municipal Council (CMC). The primary objective of the study was to develop a dependable wastewater transfer solution where conventional gravity flow was not feasible due to site constraints and existing urban infrastructure.

The methodology involved assessing projected wastewater generation based on hospital operational requirements and conducting hydraulic analyses to determine friction losses, minor losses, static head, and total dynamic head (TDH). Based on these evaluations, a 438 m long force main comprising 160 mm diameter High-Density Polyethylene (HDPE) PE100 PN10 pipes was designed to convey wastewater from the hospital pumping facility to the existing CMC sewer network. Appropriate valve chambers incorporating gate valves, non-return valves, air release valves, and scour valves were also integrated to enhance operational safety and maintainability. The hydraulic assessment indicated that the system could operate efficiently with a relatively low static lift of 2.408 m, enabling the selection of submersible pumps for reliable wastewater conveyance. The proposed arrangement provides adequate hydraulic performance, operational flexibility, and long-term serviceability within a densely developed urban environment. The study concludes that the adopted force main sewer system offers a practical, sustainable, and technically effective solution for wastewater management in urban healthcare facilities where gravity drainage systems are constrained.

Keywords: Force Main Sewer, HDPE Pipeline, Wastewater Conveyance, Hydraulic Design, Urban Healthcare Infrastructure.

2.0 Introduction

Hospitals represent critical urban infrastructure requiring uninterrupted wastewater disposal. Wastewater from wards, laboratories, kitchens, and other service areas must be conveyed hygienically and reliably to prevent environmental contamination and public health risks. In densely developed urban environments, conventional gravity sewer systems are often constrained by flat terrain, existing underground utilities, restricted working space, and complex site conditions. Under such circumstances, pressure sewer systems utilizing force main pipelines provide an effective and reliable alternative where gravity flow cannot be maintained.

The Ayurveda National Hospital, Colombo 08, experienced a significant increase in wastewater generation following the expansion of its healthcare facilities. Due to site-specific constraints and the limitations associated with conventional gravity drainage; the implementation of a force

main sewer system was identified as the most suitable wastewater conveyance solution.



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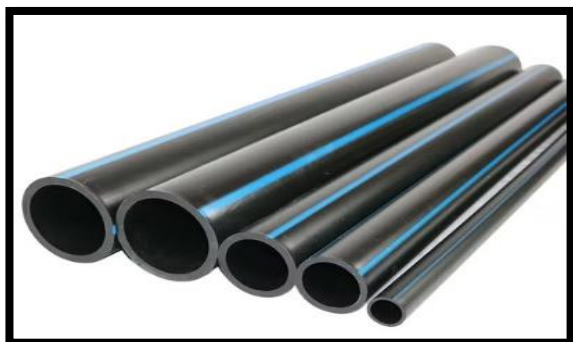
The aim of this study is to present the design and planned implementation of a force main sewer connection system for the Ayurveda National Hospital, Colombo 08, as a practical solution for wastewater conveyance in a constrained urban environment.

The specific objectives of the study are:

1. To assess the wastewater conveyance requirements of the hospital based on projected operational demands.
2. To develop an appropriate force main sewer system using HDPE pipelines and associated appurtenances.
3. To perform hydraulic analyses for determining flow characteristics, head losses, and pumping requirements.
4. To evaluate the suitability of the proposed system in terms of operational reliability, maintainability, and long-term serviceability.
5. To demonstrate the applicability of force main sewer systems for urban healthcare facilities where conventional gravity drainage is not feasible.

2.0 Project Background and Site Conditions

The Ayurveda National Hospital of Sri Lanka, commonly referred to as the Borella Ayurveda Teaching Hospital, is situated in Colombo 08 and serves as the country's primary institution for traditional medical treatment and education. A major building expansion comprising two multi-story reinforced concrete structures was completed in 2018, resulting in a substantial increase in wastewater production.



The sewer force main system was designed by the Colombo Municipal Council and awarded to Tri K Holdings (Pvt) Ltd for construction. The project site is located within a densely developed urban corridor characterized by restricted working space and numerous existing underground services.

Continuous gravity discharge was not feasible along the full pipeline alignment; therefore, a pressurized force main conveyance system was adopted. Construction activities are expected to commence upon approval and implementation of the proposed project.

3.0 Force main Sewer Pipeline - Concept and Functional Role

A force main sewer pipeline is a closed, pressurized conduit used to transfer wastewater from a lower elevation point to a higher discharge location or to a downstream gravity sewer system. Wastewater is mechanically pumped through the pipeline, allowing routing flexibility and suitability for congested urban environments where conventional gravity flow cannot be achieved.

4.0 HDPE PN10 Pipes - Material Characteristics and Suitability

HDPE PN10 pipes are manufactured from PE100 grade polyethylene and are designed to operate under a nominal working pressure of 10 bar at standard ambient conditions. The material provides high tensile strength, flexibility and excellent resistance to chemical, biological and environmental degradation associated with wastewater conveyance.

The smooth internal bore of HDPE pipes minimizes frictional resistance, thereby improving hydraulic efficiency and reducing pumping energy demand. Jointing is typically carried out using butt fusion or electrofusion methods, producing continuous homogenous joints that eliminate leakage risks. When properly designed and installed, HDPE PN10 pipeline systems are capable of achieving service lives exceeding five decades [provide reference].

5.0 Design Standards and Criteria

The sewer force main network was developed in accordance with the Colombo Municipal Council (CMC) Sewerage Design Guidelines, ISO 4427 requirements for polyethylene pressure pipes, ISO 21307 requirements for HDPE pipe fusion jointing, and accepted wastewater conveyance engineering practices. The principal design parameters and adopted criteria are summarized in below table.

These standards and criteria were used to ensure hydraulic efficiency, structural adequacy, operational safety, and long-term service reliability.

Design Parameter	Adopted Value / Criterion	Standard / Reference
Minimum Flow Velocity	≥ 0.75 m/s	CMC Sewerage Design Guidelines / Wastewater Design Practice
Maximum Flow Velocity	≤ 3.0 m/s	CMC Sewerage Design Guidelines / International Sewer Design Recommendations
Pipe Material	HDPE PE100	ISO 4427
Pipe Pressure Rating	PN10 (10 bar)	ISO 4427
Design Life	50 years (minimum)	ISO 4427 / Manufacturer Specifications
Pipe Diameter	160 mm	Hydraulic Design Calculations
Static Head	2.408 m	Project Hydraulic Analysis
Total Dynamic Head (TDH)	Calculated based on system requirements	Hydraulic Analysis
Joining Method	Butt Fusion / Electrofusion	ISO 21307
Valve Chambers	Gate Valve, NRV, Air Valve, Scour Valve	CMC Standard Details / Industry Practice

Flow velocity limits were carefully selected to maintain self-cleansing conditions within the pipeline while minimizing pipe wall wear, hydraulic shock, and unnecessary energy losses. A minimum flow velocity of **0.75 m/s** was adopted to prevent sediment accumulation and maintain self-cleansing conditions within the force main. The maximum flow velocity was limited to **3.0 m/s** to control abrasion, turbulence, excessive head loss, and potential damage to pipeline components. These velocity limits were selected in accordance with recognized pressure sewer design recommendations and accepted engineering practice to ensure stable hydraulic performance under varying operational conditions.

Internal pressure capacities were established by evaluating the combined effects of static head, frictional resistance and transient surge pressures

resulting from pump start-up and shutdown cycles. HDPE PN10 pipes manufactured from PE100 grade polyethylene were selected to provide sufficient structural strength and an adequate safety margin against internal pressure variations, thereby ensuring resistance to fatigue and long-term service integrity.

Material durability was addressed by selecting HDPE pipelines due to their superior resistance to corrosion, chemical attack, biological degradation and abrasion associated with wastewater conveyance. The inherent flexibility of the pipe material allows it to accommodate minor soil movement and settlement without joint failure. Butt-fusion jointing was adopted to produce continuous, leak-free connections, minimizing the risk of infiltration, exfiltration and long-term structural deterioration.

Hydraulic performance was further optimized through the use of smooth internal pipe surfaces, which offer low roughness values and thereby reduce frictional resistance and pumping energy requirements. Proper pipe diameter selection also contributed to maintaining stable flow regimes and minimizing operational energy consumption throughout the service life of the system.

Long-term maintainability was ensured through the installation of strategically located valve chambers equipped with gate valves, non-return valves, air release valves and scour valves. These components enable effective system isolation, air control, sediment flushing and controlled drainage during inspection, maintenance and emergency situations. Collectively, these design provisions enhance accessibility, operational flexibility and reduce overall life-cycle maintenance costs while ensuring sustainable wastewater conveyance for the hospital facility.

6.0 Hydraulic Design Methodology

Wastewater discharge quantities were assessed by considering hospital occupancy, bed capacity, outpatient attendance, and the operational functions of key service areas including wards, laboratories, operating theatres, kitchens, and sanitary installations. A per-capita wastewater generation rate of approximately 250–450 L/bed/day, consistent with commonly adopted hospital wastewater design recommendations, was used to estimate average daily wastewater flows. Suitable peak factors were applied to account for hourly fluctuations and maximum instantaneous discharge conditions. This methodology ensured that the sewer system was adequately sized to

accommodate both routine operational flows and peak loading conditions without causing surcharge or hydraulic instability.

Comprehensive hydraulic analysis was conducted along the entire force main alignment to quantify frictional resistance, minor head losses and elevation head. Friction losses were determined based on internal pipe diameter, surface roughness characteristics and flow velocity. Minor losses were evaluated for bends, fittings, valves and inlet–outlet transitions. The elevation head was calculated from the vertical difference between the pump discharge point and the downstream gravity sewer connection. The combined effect of elevation head, frictional resistance and minor losses was used to establish the total dynamic head (TDH), representing the overall hydraulic resistance to be overcome by the pumping system. The hydraulic calculations were performed manually using standard engineering equations and accepted hydraulic design procedures for pressure sewer systems.

Submersible wastewater pumps were selected in accordance with the computed TDH and required discharge capacity. These pumps were adopted due to their dependable performance, compact configuration and suitability for applications involving relatively low static lift, which are typical in urban healthcare environments. Their submerged installation enables effective motor cooling, lower noise emission and simplified installation, while ensuring stable hydraulic operation and sustained long-term efficiency of the force main sewer system.

7.0 Valve Chambers and Appurtenances



Figure- 03-Gate Valve

Gate valves are mechanically operated isolation devices that control wastewater flow by moving a flat closure element in a straight-line motion. In the fully open position, the gate is raised completely out of the flow stream, resulting in very low hydraulic resistance. When the valve is closed, the gate presses firmly against the sealing surfaces to create a watertight shut-off, enabling effective isolation of pipeline sections. These valves are primarily installed

for on–off control purposes and are not designed for regulating or throttling flow rates.



Figure- 04- Non-Return Valve

Non-return valves are self-acting devices that permit wastewater to move in only one direction while automatically blocking any reverse movement. Their primary function is to safeguard pumps and pipelines from potential damage resulting from backflow, pressure fluctuations and hydraulic shock that may occur during pump shutdown conditions.



Figure- 05- Air Valve

Air valves are fitted to expel accumulated air pockets and to allow air to enter the pipeline when negative pressure conditions occur. These valves help prevent air binding, minimize hydraulic resistance and protect the pipeline from excessive pressure variations and vacuum-related stresses. Combination air valves are commonly positioned at elevated points along the pipeline alignment and near pump discharge outlets.



Figure- 06- Scour Valve

Scour valves, also known as washout valves, are installed at low points of the force main to facilitate controlled draining and flushing. They allow removal of accumulated sediments and enable partial or complete emptying of the pipeline during maintenance and commissioning.

8.0 Pressure Testing and Commissioning of the Force Main Line

After completion of pipe installation, jointing works and fixing of all associated fittings, the sewer force main was subjected to pressure testing and commissioning procedures to confirm its mechanical strength, watertightness and functional reliability. The testing programme covered the full pipeline length, including all VJ couplings, valves, fittings and related accessories. Before commencing the test, the pipeline was thoroughly flushed to remove any residual construction debris and sediments. Air release valves were fully opened to discharge trapped air pockets, ensuring accurate pressure readings and eliminating the possibility of false pressure losses. The pipeline was then filled with clean water and allowed to stabilize prior to initiating the pressure testing process.

Hydrostatic testing is proposed to be conducted at a pressure level not less than the pipe manufacturer's recommended test pressure and in accordance with the Engineer's requirements. For the selected HDPE PN10 pipeline, the recommended hydrostatic test pressure is expected to be approximately 1.5 times the normal operating pressure, subject to final approval during commissioning.

If any defects were observed, immediate corrective measures were undertaken and the testing cycle was repeated until satisfactory results were obtained. Recorded pressure loss values were evaluated against allowable limits to confirm compliance with the relevant design criteria.

Following successful completion of testing, final flushing and commissioning procedures were carried out to place the force main into operational service. These activities ensured that the pipeline system was secure, leak-free and hydraulically stable for long-term wastewater transportation.

9.0 Health, Safety and Environmental Considerations

Given that the project is situated within an active hospital environment, safety planning formed a critical component of construction management. Protective measures such as trench support systems, traffic control arrangements, site barricading and mandatory use of personal protective equipment were implemented to safeguard workers, hospital staff and the public. Valve chambers were managed as confined workspaces, with adequate access provisions and ventilation measures to ensure safe entry and operation.

Environmental safeguarding was achieved through the use of leak-proof HDPE pipeline joints, which minimize the risk of wastewater escape, together with controlled discharge procedures adopted during flushing and commissioning activities to prevent contamination of the surrounding environment.

10.0 Constructability Considerations

Construction planning was carried out with careful consideration of restricted working space and the requirement to keep hospital services operating without interruption. The flexible nature of HDPE piping enabled installation within narrow and congested service corridors, while a staged construction sequence was adopted to reduce disturbance to ongoing hospital activities.

11.0 Conclusions

The developed sewer force main scheme offers a dependable, long-lasting and secure wastewater conveyance solution for the Ayurveda National Hospital of Sri Lanka. Planned by the Colombo Municipal Council and implemented by Tri K Holdings (Pvt) Ltd, the project illustrates an efficient and practical model for managing wastewater infrastructure within densely built urban healthcare environments.

12.0 Discussion

The proposed force main sewer system was developed to provide a reliable wastewater conveyance solution for the Ayurveda National Hospital under constrained urban site conditions. Although the project had completed the tendering stage at the time of writing, construction, pressure testing, and commissioning activities had not yet commenced. Therefore, the discussion presented herein is based on the design evaluation and anticipated operational performance of the proposed system.

The hydraulic design indicated that the selected 160 mm diameter HDPE PE100 PN10 pipeline is capable of conveying the projected wastewater flows while maintaining acceptable flow velocities and pressure conditions. The calculated total dynamic head (TDH) and relatively low static lift of 2.408 m support the suitability of submersible pumps for efficient system operation. Based on the design calculations, the proposed arrangement is expected to satisfy the required hydraulic performance criteria and provide dependable service under normal operating conditions.

Upon construction completion, hydrostatic pressure testing will be carried out in accordance with the Engineer's requirements and relevant specifications to verify the structural integrity, watertightness, and operational reliability of the pipeline system. The test results will be compared against the design expectations to confirm compliance with the specified performance requirements.

A key advantage of the proposed design is its ability to provide effective wastewater conveyance in locations where conventional gravity sewer systems are impractical due to limited gradients, underground utility congestion, and restricted working space. The use of HDPE pipes offers additional benefits, including corrosion resistance, flexibility, leak-free fusion joints, and long service life. However, the system is dependent on continuous pump operation and electrical power availability, which may require standby arrangements to ensure uninterrupted service. The design approach adopted in this study may be applied to other urban healthcare facilities facing similar site constraints and wastewater management challenges. Lessons learned during the planning and design stages highlighted the importance of detailed utility investigations, careful hydraulic assessment, and the provision of adequate valve chambers to facilitate operation and maintenance. The primary challenges encountered during project development included restricted working space, the

presence of existing underground services, and the need to minimize disruption to hospital operations. These challenges were addressed through careful route selection, the adoption of HDPE pipeline technology, and the incorporation of appropriate operational and maintenance features within the overall system design.

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Pre-cast Concrete for Vertical Farming: A Structural Solution for Land-Scarce Colombo

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Abstract: Rapid urbanization in the Colombo Metropolitan Area has resulted in increasing population density, rising land values, and significant reductions in land available for conventional agricultural activities. These challenges have intensified concerns regarding urban food security, sustainable resource utilization, and efficient land management. Vertical farming has emerged as an innovative urban agricultural approach that enables crop production within multi-storey structures while maximizing productivity per unit land area. However, the structural feasibility, durability, and long-term performance of such facilities remain critical considerations. This study presents a conceptual feasibility assessment of pre-cast concrete construction systems as a structural solution for vertical farming developments in Colombo. The assessment is based on a comprehensive review of peer-reviewed literature, established structural engineering principles, and urban development challenges relevant to Sri Lanka. Key parameters including structural capacity, durability, construction efficiency, adaptability, and sustainability were evaluated to determine the suitability of pre-cast concrete systems for supporting vertical farming infrastructure. The analysis indicates that vertical farming facilities impose substantially higher structural demands than conventional buildings due to growing racks, planting media, water storage systems, irrigation networks, and environmental control equipment. The findings suggest that pre-cast concrete systems offer several advantages, including high load-bearing capacity, improved quality control through factory-controlled production, rapid construction, reduced on-site disruption, enhanced durability under moisture-rich operating conditions, and flexibility for modular expansion. Furthermore, the integration of pre-cast concrete and vertical farming has the potential to support sustainable urban development through efficient land utilization, reduced construction waste, and improved urban food production capacity. The study concludes that pre-cast concrete provides a practical and sustainable structural framework for integrating vertical farming into land-scarce urban environments such as Colombo. The findings contribute to the growing body of knowledge on sustainable urban agriculture and provide a foundation for future structural modelling and quantitative assessment studies in Sri Lanka.

Key Words: Vertical Farming, Pre-cast Concrete, Urban Agriculture, Urban Land Scarcity, Sustainable Construction.

3.0 Introduction

Rapid urbanization in the Colombo Metropolitan Area has led to a continuous increase in population density, driven by migration and concentrated settlement within the city. This rapid urban growth has intensified land scarcity, significantly limiting the availability of land for conventional horizontal agricultural practices. As a result, urban food systems are facing increasing pressure, raising critical concerns related to food security, sustainable resource management, and efficient land utilization in densely populated environments.

Traditional farming methods, which rely on extensive land availability, are becoming increasingly inadequate to meet the growing food demand of urban populations. This limitation highlights the urgent need for innovative, space-efficient, and sustainable agricultural solutions that can be integrated within the urban built environment.

Vertical farming has emerged as a promising alternative approach that enables agricultural production within multi-storey building systems through the vertical stacking of cultivation units. This

system enhances land-use efficiency by maximizing crop yield per unit area while also offering additional benefits such as reduced water consumption, decreased transportation dependency, and year-round controlled production. Despite these advantages, the widespread implementation of vertical farming in urban environments is constrained by critical engineering challenges, particularly related to structural load demands, service integration, durability under high-moisture conditions, and overall construction feasibility.

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In this context, structural systems play a key role in determining the viability of vertical farming infrastructure. Precast concrete construction offers potential advantages such as high load-bearing capacity, rapid construction, modular adaptability, and superior quality control, making it a strong candidate for supporting such high-demand building systems in dense urban settings.

Figure 3: Conceptual integration of pre-cast concrete structural systems with vertical farming infrastructure (Author developed).



The primary aim of this paper is to conceptually evaluate the suitability of pre-cast concrete as a structural solution for vertical farming developments in the Colombo Metropolitan Area. The study addresses the following research question:

Can pre-cast concrete provide an efficient, durable, and sustainable structural framework to support vertical farming in land-scarce urban environments?

This study emphasizes the significance of this approach by:

- a. Proposing a structural engineering-based solution to address urban land scarcity in agriculture.
- b. Exploring the integration of pre-cast concrete technology with vertical farming systems.
- c. Contributing to sustainable urban development and food security strategies in Sri Lanka.

By adopting a conceptual methodology grounded in established structural engineering principles and existing literature, this paper develops a framework for understanding how pre-cast concrete systems can enhance the feasibility, efficiency, and sustainability, of vertical farming infrastructure in Colombo. The findings are expected to support future research, structural design development, and policy-level planning for urban agricultural systems in land-constrained metropolitan regions.

4.0 Literature Review

2.1 Urban Agriculture and Vertical Farming

Rapid urbanization has significantly reduced the availability of agricultural land in many cities worldwide, creating challenges for food security and sustainable urban developments. As urban populations continue to increase, innovative approaches to food production have become increasingly important. Urban agriculture has emerged as a strategy for improving local food production while reducing dependence on food transported from rural areas (Udawattha, 2023).

Among the various forms of urban agriculture, vertical farming has gained considerable attention due to its ability to maximize agricultural output within limited land areas. Despommier (2010) introduced the concept of vertical farming as a system where crops are cultivated within vertically stacked layers under controlled environmental conditions. This approach allows year-round crop production while reducing land requirements and minimizing the impacts of adverse climatic conditions.

Benke and Tomkins (2017) reported that vertical farming systems can significantly improve resource-use efficiency through controlled irrigation, nutrient management, and environmental regulation. Similarly, Oh and Lu (2022) identified vertical farming as a promising solution for future food production due to its ability to reduce water consumption, improve crop productivity, and enhance urban food security. Recent developments in automation, environmental monitoring, and smart farming technologies have further increased the operational efficiency of vertical farming systems (Chowdhury et al., 2023).

Despite these advantages, vertical farming facilities require substantial infrastructure investments and must accommodate significant structural loads associated with cultivation systems, water storage, environmental control equipment, and maintenance activities. Consequently, the selection of an appropriate structural system is critical for the successful implementation of vertical farming projects.

2.2 Structural Requirements of Vertical Farming Facilities

Unlike conventional commercial or residential buildings, vertical farming facilities are subjected to unique structural demands resulting from agricultural operations conducted within multi-storey environments. These facilities typically contain

growing racks, hydroponic or aeroponic cultivation systems, water storage tanks, irrigation networks, artificial lighting systems, and heating, ventilation, and air-conditioning (HVAC) equipment.

According to Al-Kodmany (2018), vertical farming buildings require structural systems capable of supporting higher floor loads while maintaining flexibility for changing agricultural technologies and future expansion. Water storage systems and irrigation networks contribute additional loads that must be considered during structural design. Furthermore, the high-moisture environments commonly associated with indoor farming operations may accelerate material deterioration if unsuitable construction materials are used.

Structural durability is therefore an important consideration in vertical farming developments. Long-term exposure to moisture, temperature fluctuations, and operational loading cycles requires robust structural systems capable of maintaining performance throughout their service life. Consequently, construction materials must provide adequate strength, durability, and resistance to environmental degradation.

2.3 Pre-cast Concrete Technology in Modern Construction

Pre-cast concrete construction has become increasingly popular worldwide due to its ability to improve construction efficiency, quality control, and sustainability. Pre-cast concrete components are manufactured under controlled factory conditions and transported to the construction site for assembly.

Tam et al. (2007) identified pre-fabrication technologies as an effective means of reducing construction duration, improving productivity, and minimizing material waste. Factory-controlled manufacturing environments enable higher quality standards and improved dimensional accuracy compared with conventional cast-in-situ construction methods.

Kwon et al. (2018) demonstrated that pre-cast concrete systems provide excellent structural performance and durability under demanding environmental conditions. Similarly, Martins et al. (2023) highlighted recent advancements in pre-cast concrete technology that enhance structural efficiency, sustainability, and long-term performance. The modular nature of pre-cast concrete construction also allows rapid assembly and flexibility in building design, making it particularly suitable for projects requiring repetitive structural layouts.

These characteristics suggest that pre-cast concrete systems may provide significant advantages for vertical farming facilities, where repetitive floor arrangements, large open spaces, and rapid construction are often desirable.

2.4 Sustainability Benefits of Pre-cast Concrete Construction

Sustainability has become a major consideration in modern construction practices. Sustainable construction aims to minimize environmental impacts while maximizing economic and social benefits throughout a building's life cycle.

Figure 2: Sustainability benefits associated with pre-cast concrete construction (Author developed)



Kibert (2016) emphasizes that sustainable construction involves efficient resource utilization, waste reduction, and improved building performance. Pre-cast concrete construction contributes to these objectives through factory-controlled production processes that optimize material usage and reduce construction waste.

Gallo et al. (2021) found that pre-cast concrete systems can reduce environmental impacts through improved production efficiency and reduced on-site activities. Likewise, Tavares et al. (2021) reported that industrialized pre-cast construction methods provide both environmental and economic benefits by shortening project durations and improving construction productivity.

When integrated with vertical farming systems, pre-cast concrete construction may further contribute to sustainability objectives by supporting urban food production while reducing transportation requirements and associated carbon emissions.

2.5 Urban Development Challenges in Colombo

The Colombo Metropolitan Area is experiencing rapid urbanization, increasing population density, and growing pressure on available land resources. Rising land values and competing demands for residential, commercial, and infrastructure development have

significantly reduced the availability of land for conventional agricultural activities. Sustainable construction practices are increasingly being recognized as an important component of urban development in Sri Lanka (wijewardane and Jayasinghe, 2019). These challenges have raised concerns regarding urban food security, sustainable land utilization, and climate resilience within the city.

Urban agriculture has been identified as a potential strategy for improving food production while enhancing environmental sustainability in densely populated urban areas. Udawattha (2023) highlights urban agriculture as an important approach for promoting climate resilience and sustainable urban development in Colombo. Similarly, Kulathunga et al. (2023) noted that urban farming can contribute to urban food security; however, its implementation is often constrained by challenges related to building design, infrastructure requirements, technological limitations, and associated costs. Given the increasing demand for food and the limited availability of urban land, vertical farming has emerged as a promising solution for Colombo. By enabling agricultural production within multi-storey structures, vertical farming can significantly improve land-use efficiency while reducing dependence on conventional farming land. Furthermore, controlled-environment agriculture can support year-round crop production and improve the resilience of urban food systems.

However, the successful implementation of vertical farming requires structural systems capable of supporting increased operational loads arising from growing racks, planting media, water storage systems, irrigation networks, and environmental control equipment. Structural durability, adaptability, and efficient construction methods are also important considerations in dense urban environments where space constraints and construction-related disruptions must be minimized. Therefore, identifying suitable structural solutions is essential for the practical implementation of vertical farming developments in Colombo. Pre-cast concrete systems offer several potential advantages, including high load-bearing capacity, durability, construction efficiency, and modular adaptability, making them a promising structural option for supporting sustainable urban agricultural infrastructure.

Figure 3: Urban development Challenges in the Colombo Metropolitan Area (Author developed).



2.6 Research Gap

A review of existing literature indicates that considerable research has been conducted separately on vertical farming technologies and pre-cast concrete construction systems. Studies have examined the benefits of controlled-environment agriculture, urban food production, construction sustainability, and prefabricated building technologies. However, limited research has investigated the integration of pre-cast concrete systems with vertical farming facilities, particularly within the context of Sri Lanka and the Colombo Metropolitan Area. Furthermore, there is a lack of studies evaluating the suitability of pre-cast concrete as a structural solution for supporting the increased loading requirements, durability demands, and sustainability objectives associated with vertical farming developments. This study addresses this research gap by conceptually assessing the compatibility of pre-cast concrete technology with the structural and operational requirements of vertical farming infrastructure in Colombo. The identified research gaps and the contribution of this study are summarized in Table 1.

Table 1: The identified research Gaps and the contribution of this paper

Aspect	Existing Studies	Contribution of This Study
Urban Agriculture in Sri Lanka	Focus on small-scale systems	Focus on vertical farming systems
Structural Engineering Integration	Limited consideration	Pre-cast concrete evaluation for farming structures
Technological Development	Emerging IoT/automation adoption	Structural implication of smart farming systems
Urban Context	General global studies	Colombo-specific land scarcity focus
Research Approach	Isolated disciplinary studies	Inter-disciplinary engineering framework

3.0 Methodology

This study adopts a conceptual qualitative methodology to evaluate the suitability of pre-cast concrete as a structural solution for vertical farming developments in the Colombo Metropolitan Area. The research is based on a systematic review and analysis of existing literature, established engineering principles, and urban development conditions rather than experimental testing of field investigations. The methodology was developed to provide a logical framework for assessing the compatibility of pre-cast concrete systems with the structural and functional requirements of vertical farming facilities.

3.1 Research Approach

A conceptual research approach was selected due to the emerging nature of integrating pre-cast concrete technology with vertical farming systems in the Sri Lankan urban context. Limited local studies have examined the relationship between structural engineering solutions and vertical farming infrastructure. Therefore, the study relies on:

- Established structural engineering principles.
- Peer-reviewed literature related to vertical farming and pre-cast concrete systems
- Urban development challenges associated with land scarcity in Colombo

This approach enables the evaluation of innovative engineering concepts where empirical data are currently limited.

3.2 Literature-Based Analysis

A comprehensive review of peer-reviewed journal articles, conference proceedings, technical reports, and academic publications was undertaken to identify current knowledge and developments related to:

- Vertical farming technologies and infrastructure
- Structural requirements of vertical farming facilities
- Characteristics and performance of pre-cast concrete construction systems
- Sustainable urban development and urban agriculture

Particular emphasis was placed on recent studies published after 2020 to ensure the relevance of findings to current engineering and construction practices. The reviewed literature was critically analyzed to identify key themes, benefits, limitations, and research gaps relevant to the study objectives.

3.3 Identification of structural Requirements for Vertical Farming

The functional and structural requirements of vertical farming facilities were identified through a synthesis of published literature and engineering design considerations. Key requirements include:

- High floor load capacity to support growing racks, planting media, water storage, and service systems
- Structural flexibility for modular layouts and future expansion
- Durability under high-moisture and controlled-environment conditions
- Efficient integration of mechanical, electrical, plumbing, and irrigation systems

Table 2 summarizes the principal load categories associated with vertical farming facilities and their implications for structural design.

Table 2: Typical Structural Loads in Vertical Farming Facilities

Load Type	Description	Structural Significance
Dead Load	Self-weight of slabs, beams, columns, and structural components	Governs structural member sizing
Live Load	Workers, maintenance activities, and movable equipment	Influences safety and serviceability requirements
Farming Load	Growing racks, planting media, cultivation systems	Higher than conventional floor loading
Water Load	Water storage and irrigation systems	Requires enhanced slab capacity
Service Load	HVAC systems, lighting, piping, and automation equipment	Requires integration into structural design

These requirements formed the basis for evaluating the suitability of pre-cast concrete systems.

3.4 Conceptual Evaluation of Pre-cast Concrete Systems

Pre-cast concrete systems were conceptually evaluated against the identified structural and operational requirements of vertical farming facilities. The evaluation focused on the following performance criteria:

- Structural load-bearing capacity
- Construction efficiency and speed
- Quality control and durability
- Adaptability to modular building configurations
- Long-term maintenance performance

The evaluation was conducted through comparative analysis using findings reported in existing literature and accepted engineering principles.

3.4.1 Conceptual Evaluation Matrix

To provide a systematic assessment of the suitability of pre-cast concrete systems for vertical farming developments, a conceptual evaluation matrix was developed based on key structural and operational requirements identified from the literature. The evaluation criteria included structural capacity, durability, construction efficiency, modularity, sustainability and maintenance performance.

Table 3: Conceptual Evaluation Matrix for Pre-cast Concrete in Vertical Farming Applications

Evaluation Criterion	Importance Level	Assessment of Pre-cast Concrete
Structural Capacity	High	Suitable
Durability in Moist Conditions	High	Suitable
Construction Speed	Medium	Suitable
Quality Control	High	Highly suitable
Modularity and Expandability	High	Highly suitable
Maintenance Requirements	Medium	Suitable
Sustainability Performance	High	Suitable

The evaluation indicates that pre-cast concrete systems satisfy most of the critical requirements associated with vertical farming facilities and therefore represent a promising structural solution for land-constrained urban environments.

3.5 Contextual Assessment for the Colombo Metropolitan Area

To enhance the practical relevance of the study, urban development conditions specific to the Colombo Metropolitan Area were considered. The assessment focused on:

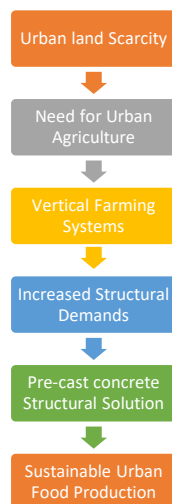
- High land values and limited land availability
- Dense urban development and site constraints
- Increasing demand for sustainable food production systems
- The need for efficient construction methods that minimize urban disruption

The potential advantages of pre-cast concrete systems in addressing these challenges were examined within the context of vertical farming development.

3.6 Analytical Framework

The analytical framework developed for this study establishes a logical relationship between urban challenges, structural requirements, and engineering solutions, as illustrated below:

Figure 4 : Conceptual framework linking urban land scarcity, vertical farming requirements and pre-cast concrete as a structural solution (Author developed).



This framework guided the evaluation process and supported the development of the study's conclusions.

3.7 Validation of Findings

The findings of the study were validated through:

- Consistency with established structural engineering theory
- Agreement with Conclusions reported in peer-reviewed literature
- Logical alignment between identified urban challenges and the proposed engineering solution.

Although experimental validation was beyond the scope of this study, the methodology provides a credible basis for future quantitative investigations and pilot-scale implementations.

3.8 Limitations of the Study

This research is limited to a conceptual evaluation and does not include structural design calculations, finite element modeling, cost analysis, life-cycle assessment, or experimental testing. Consequently, the findings should be interpreted as a preliminary engineering assessment. Future studies should incorporate detailed structural analysis, economic evaluation, and practical implementation to further validate the proposed concept.

4.0 Conceptual Structural Assessment and Discussion

The successful implementation of vertical farming facilities depends not only on agricultural technologies but also on the ability of the structural system to safely support operational loads. Unlike conventional commercial buildings, vertical farming structures are subjected to additional loads arising from growing racks, planting media, water storage systems, irrigation networks, and environmental control equipment.

Based on values commonly reported in literature for controlled-environment agriculture facilities, the typical floor loading requirements for a vertical farming building can be conceptually estimated as shown in Table 4.

The values presented in Table 4 are indicative estimates synthesized from loading ranges reported in vertical farming and controlled-environment agriculture literature and are intended solely for conceptual comparison purposes. (Adapted from Al-Kodmany, 2018; Oh, and Lu, 2022).

Table 4: Indicative Loading Components for Vertical Farming Facilities

Load Component	Estimated Load (kN/m ²)
Growing racks and support systems	1.5
Planting media and crops	0.8
Water storage and irrigation systems	2
Maintenance and operational activities	2
Mechanical and electrical services (HVAC, lighting, piping)	1.2
Total Estimated Load	7.5

The estimated total operational load of approximately 7.5 kN/m² is considerably higher than the loading typically associated with conventional office buildings, where imposed floor loads commonly range between 3.0 and 5.0 kN/m². This comparison highlights the need for structural systems capable of supporting increased loading demands while maintaining safety, serviceability, and long-term durability.

To further evaluate the suitability of pre-cast concrete systems for vertical farming applications, a comparison was conducted between conventional cast-in-situ reinforced concrete construction and pre-cast concrete construction based on key performance criteria relevant to vertical farming facilities. The comparison focuses on construction efficiency, quality control, waste generation, durability, modularity, and overall suitability for supporting the operational requirements of vertical farming developments.

Table 5: Comparison between Conventional Reinforced Concrete and Pre-cast Concrete Systems for Vertical Farming

Parameter	Conventional Reinforced Concrete	Pre-cast Concrete
Construction Speed	Moderate	High
Quality Control	Site-dependent	Factory-controlled
Waste Generation	Higher	Lower
Labour Requirements	High	Moderate
Site Congestion	High	Low
Parameter	Conventional Reinforced Concrete	Pre-cast Concrete
Durability	Moderate	High
Modularity	Limited	Excellent
Maintenance Requirements	Moderate	Low
Suitability for Vertical Farming	Moderate	High

As shown in Table 5, pre-cast concrete systems demonstrate several advantages over conventional cast-in-situ reinforced concrete construction for vertical farming applications. Factory-controlled production enhances quality consistency and reduces material wastage, while modular construction facilitates rapid installation and future expansion. Furthermore, the superior durability and reduced maintenance requirements of pre-cast concrete make it particularly suitable for the moisture-rich environments typically associated with vertical farming facilities. These advantages support the potential application of pre-cast concrete as a sustainable and efficient structural solution for vertical farming developments in the Colombo Metropolitan Area.

Pre-cast concrete systems possess several characteristics that make them suitable for such applications. Their high load-bearing capacity allows efficient support of increased floor loads associated with vertical farming operations. Factory-controlled production enhances quality consistency and dimensional accuracy, while modular construction facilitates repetitive building layouts commonly required for vertical farming facilities.

Furthermore, pre-cast concrete construction can significantly reduce on-site construction time, which is particularly advantageous in densely developed urban areas such as Colombo where construction activities may cause traffic congestion and operational disruptions. The durability of pre-cast concrete under humid environmental conditions also contributes to reduced maintenance requirements and improved long-term performance.

The relationship between urban challenges, vertical farming requirements, and pre-cast concrete solution can be summarized as follows:

Urban Land Scarcity → Need for Urban Agriculture → Vertical Farming Systems → Increased Structural Loads and Service Requirements → Precast Concrete Structural Solution → Sustainable Urban Food Production Based on this conceptual assessment, pre-cast concrete systems demonstrate strong potential as a structural framework for vertical farming developments in land-constrained urban environments. Although detailed structural design and economic analysis are beyond the scope of this study, the findings indicate that pre-cast concrete technology can effectively address many of the engineering challenges associated with vertical farming infrastructure.

5.0 Conclusions

This study examined the suitability of pre-cast concrete technology as a structural solution for vertical farming developments within the land-scarce urban context of the Colombo Metropolitan Area. Through a systematic evaluation based on established structural engineering principles, peer-reviewed literature, urban development challenges, and a conceptual assessment of vertical farming loading requirements, the study investigated the compatibility of pre-cast concrete systems with the functional and structural demands of vertical farming facilities.

The findings indicate that vertical farming infrastructure imposes substantially higher structural demands than conventional building applications due to the presence of growing racks, planting media, water storage systems, irrigation networks, and environmental control equipment. The conceptual loading assessment demonstrated that these facilities require structural systems capable of supporting increased floor loads while maintaining durability, serviceability, and long-term performance.

When evaluated against these requirements, pre-cast concrete systems exhibit several advantages, including high load-bearing capacity, durability, quality-controlled manufacturing, rapid construction, and adaptability to modular building configurations. These characteristics make pre-cast concrete particularly suitable for vertical farming developments, where repetitive layouts, efficient construction processes, and reliable structural performance are essential.

Figure 5: Key advantages of pre-cast concrete systems for sustainable vertical farming facilities (Author developed).



The analytical framework developed in this study established a logical relationship between urban land scarcity, the need for urban agriculture, the adoption of vertical farming systems, and the suitability of pre-cast concrete as a structural solution. Within the context of Colombo, where limited land availability and increasing food demand present significant urban

development challenges, pre-cast concrete offers a practical and sustainable engineering approach for supporting future urban food production infrastructure.

This study contributes to the existing body of knowledge by integrating concepts from urban agriculture, structural engineering, and sustainable construction within a Colombo-specific context. Furthermore, it provides a conceptual foundation for future planning and implementation of vertical farming facilities in Sri Lanka and other land-constrained urban environments.

The study is limited to a conceptual evaluation and does not include detailed structural design, numerical modelling, economic assessment, or experimental validation. Therefore, future research should focus on structural analysis, life-cycle cost evaluation, environmental performance assessment, and pilot-scale implementation studies to further validate the feasibility and effectiveness of pre-cast concrete systems for vertical farming applications.

Overall, the study concludes that pre-cast concrete technology presents a viable, durable, and sustainable structural framework for vertical farming developments and has significant potential to contribute to resilient urban food production and sustainable urban development in Colombo.

Figure 6: Contribution of vertical farming to urban food resilience (Author developed).



The findings of this study may support engineers, planners, and policymakers in developing sustainable urban food production infrastructure within rapidly urbanizing cities. Consequently, the integration of pre-cast concrete technology and vertical farming may represent a viable pathway towards enhancing urban resilience, food security, and sustainable development within rapidly urbanizing cities.

Acknowledgement

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SECTION II

Transforming Post-Contract Works and Contract Management through Artificial Intelligence: The Way Forward for Sri Lanka's Construction Industry

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Abstract: The integration of Artificial Intelligence (AI) into the construction industry is transforming traditional post-contract works and contract management practices by improving efficiency, accuracy, transparency, and decision-making. AI technologies support automated contract review, risk identification, variation management, resource optimization, safety monitoring, and real-time site performance tracking, enabling a shift from mainly reactive practices to proactive project control. This paper examines the role of AI in enhancing post-contract site operations and contract administration across key engineering and built-environment disciplines, including civil, mechanical, electrical, HVAC, information technology, and architecture. Drawing on international best practices, the discussion is contextualized to be relevant to the Sri Lankan construction industry. Although AI adoption in Sri Lanka remains limited, especially in public-sector projects, ongoing national digitalization initiatives and the National Artificial Intelligence Strategy provide a policy framework for structured, phased implementation. The paper argues that strategic adoption of AI, along with Building Information Modeling (BIM), can improve transparency, reduce disputes, enhance safety, and support sustainable project delivery in Sri Lanka's construction sector.

Key Words: Artificial Intelligence (AI); Construction Contract Management; Post-Contract Works; Building Information Modelling (BIM); Construction Digitalization; Sri Lanka

1. Introduction

1.1 AI as a Catalyst for Modern Contract Management

Construction contract management encompasses the planning, execution, monitoring, and closure of contractual obligations among clients, consultants, contractors, and other stakeholders. In construction projects, post-contract responsibilities include scope control, variation management, claims administration, compliance monitoring, cost and time control, safety management, preparation of as-constructed records, commissioning, and final handover. The multidisciplinary nature of construction projects and the dynamic conditions of construction sites further increase the complexity of effective contract administration.

In Sri Lanka, contract management practices have traditionally relied on manual documentation, fragmented reporting systems, and experience-based decision-making. While these approaches have historically supported project delivery, they are increasingly inadequate for managing the scale, complexity, and accountability requirements of contemporary construction projects. Common challenges include delayed decision-making,

inconsistent documentation, limited transparency, and frequent disputes, particularly within large public-sector developments.

The rise of Artificial Intelligence (AI) has brought a fundamental shift in construction contract management. AI allows for automating repetitive administrative tasks, extracting insights from large datasets, monitoring progress in real time, and using predictive analytics for risk and performance management. Around the world, AI-powered tools such as Kira Systems (Kira Systems, 2023), LawGeex (LawGeex, 2022), Buildots (Buildots, 2022), and Disperse (Disperse, 2023) have demonstrated measurable gains in efficiency, compliance and accuracy in post-contract processes.

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In the Sri Lankan context, the adoption of AI and Building Information Modeling (BIM) remains mostly limited to select large-scale infrastructure and internationally funded private-sector projects. However, the government's broader public-sector digitalization agenda and the National Artificial Intelligence Strategy (CFSAI, 2023) offer a timely foundation for expanding AI-supported post-contract and contract management practices across the construction industry.

2. Methodology

This paper adopts a descriptive and analytical review methodology, drawing upon published academic literature, industry reports, technology provider documentation, and policy frameworks relevant to AI adoption in construction. International case studies are reviewed to identify proven AI applications in post-contract work and contract management. These applications are then contextualized for Sri Lanka by examining industry practices, institutional readiness, digital infrastructure, and national policy directions.

Rather than presenting empirical data, the study focuses on conceptual integration and practical applicability, making it particularly relevant for practitioners, policymakers, and professional institutions seeking guidance on phased AI adoption within the Sri Lankan construction industry.

3. Conceptual Analysis: Contract Management Processes and the Role of AI

Construction contract management spans the full lifecycle of a project, from contract execution through monitoring, variations, claims management, completion, and post-handover obligations. Within this lifecycle, post-contract administration plays a critical role in ensuring contractual compliance, cost and time control, quality assurance, and effective risk management.

AI enhances these processes by enabling data-driven automation and predictive analysis across contract administration functions. AI-assisted contract review tools help identify high-risk clauses, deviations from standard conditions, and potential compliance issues early, thereby reducing reliance on manual reviews. AI-driven risk analytics further

strengthen contract management by analyzing historical project data, contract provisions, and real-time site inputs to identify emerging risks (ZBrain.ai, 2024). In the Sri Lankan construction context, where disputes frequently arise from delayed decisions and ambiguous contract interpretation, such predictive capabilities can support proactive intervention and improved dispute avoidance.

4. AI in Post-Contract Site Works and Discipline-Specific Applications

4.1 Civil Engineering

In civil engineering projects, AI supports construction sequencing, scheduling, logistics planning, and progress monitoring. AI-enabled planning tools can simulate alternative construction scenarios and identify efficient sequencing strategies, supporting informed decision-making during post-contract execution (ALICE Technologies, 2023).

AI-based monitoring systems enable real-time tracking of earthworks, concrete placement, and material deliveries, generating objective progress data. For large infrastructure projects in Sri Lanka, such as highways, bridges, multi-storied buildings, and water resources developments, these capabilities can enhance progress certification, improve reporting accuracy, and reduce delays and cost overruns.

4.2 Mechanical and HVAC Systems

AI-enabled monitoring systems support predictive maintenance, system optimization, and energy-performance management for mechanical and HVAC installations. By analyzing sensor data, AI can identify performance anomalies and predict equipment failures before they occur (Honeywell Forge, 2022).

These capabilities are particularly relevant during post-contract and operation-and-maintenance phases, where reliable system performance and lifecycle cost control are critical. In Sri Lanka's hospitals, commercial buildings, and industrial facilities, AI-supported predictive maintenance can help reduce downtime and improve asset management.

4.3 Electrical Engineering

AI applications in electrical engineering include load analysis, system optimization, energy-efficiency monitoring, and compliance support. AI-assisted analysis enables engineers to optimize electrical layouts and monitor system performance in real time, supporting energy-efficient operation and regulatory compliance (Autodesk, 2022).

As Sri Lanka moves toward energy-efficient buildings and smart-grid readiness, AI-enabled electrical systems can support sustainability objectives and enhance post-contract performance verification.

4.4 Information Technology Systems and BIM Integration

The integration of AI with BIM creates a centralized platform for project coordination and contract management. AI-enhanced BIM systems can analyze model data to identify clashes, track construction progress, and assist with variation and change management (Autodesk, 2022).

During post-contract stages, AI-assisted BIM platforms enhance document control, progress certification, and version management, thereby increasing transparency and accountability. For Sri Lanka, where BIM adoption is still growing, phased integration, supported by AI analytics, provides a practical way to improve contract management.

4.5 Architectural Coordination

AI helps with architectural coordination by performing design compliance checks, managing documentation, and enabling adaptive planning. By analyzing site feedback and construction data, AI tools can pinpoint design issues that might impact post-contract execution.

In Sri Lanka's multi-agency approval environment, such capabilities can help minimize design-related delays and reduce inconsistencies during post-contract implementation.

5. AI-Enabled Coordination Among Project Stakeholders

Effective post-contract management depends on seamless coordination among clients, consultants, project managers, resident engineers, and contractors. AI facilitates this coordination through

centralized digital platforms, everyday data environments, and real-time dashboards.

Project managers and resident engineers benefit from AI-based dashboards that integrate cost, schedule, quality, safety, and variation data, enabling informed and timely decision-making (OpenSpace AI, 2023). Clients gain improved visibility and predictive insights, enhancing governance and reducing uncertainty throughout the project lifecycle (OpenSpace AI, 2023). Contractors use AI to streamline operations, optimize manpower deployment, improve safety, equipment scheduling, and procurement timelines, ensure better compliance with contractual obligations, and support decision-making (ZBrain.ai, 2024).

In the Sri Lankan context, where coordination is often hampered by manual reporting and fragmented communication, AI-based collaboration platforms provide a practical way to bridge the gap between design intent and site execution, thereby reducing disputes and enhancing accountability.

6. AI for Safety, Resource Optimization, Maintenance and Change Management

AI is increasingly applied to improve site safety, optimize resource utilization, and manage changes during post-contract stages. AI-powered safety systems that use computer vision and wearable sensors monitor worker behavior and site conditions, with studies reporting reductions in accidents of up to 30% (Triax Technologies, 2021). These applications are particularly relevant to Sri Lanka, where construction safety remains a critical industry concern. AI also enhances resource optimization by analyzing patterns in labour, material, and equipment usage. International studies report material waste reductions of up to 20% through AI-driven scheduling and logistics planning (ALICE Technologies, 2023). Predictive maintenance systems, supported by IoT sensors, reduce equipment downtime and lifecycle costs (Honeywell Forge, 2022), offering clear benefits for Sri Lankan contractors operating under tight margins.

In managing variations and changes, AI-enabled BIM systems automatically record design changes, update documentation, and maintain version

control, ensuring transparency and traceability (Autodesk, 2022). Case studies indicate reductions in approval times and design errors through AI-

supported change management (OpenSpace AI, 2023). offering valuable lessons for Sri Lankan projects.

7. Discussion

Table 1: International AI Applications in Post-Contract Management and Their Relevance to the Sri Lankan Construction Industry

Post-Contract Function	Typical AI Applications (International Practice)	Key Benefits Reported	Main Limitations	Relevance to Sri Lanka
Contract review & compliance	AI-assisted clause analysis and compliance checking	Faster reviews, early identification of contractual risks	Requires structured digital contracts	Suitable for large projects using standard forms of contract
Progress monitoring	Computer-vision-based site progress verification	Objective progress records, reduced payment disputes	High initial cost; site data dependency	Applicable to large infrastructure and donor-funded projects
Risk & claims management	Predictive analytics using historical project data	Early risk identification, dispute avoidance	Dependent on quality historical data	Medium-term applicability with improved data systems
Construction planning & scheduling	AI-based simulation of construction sequences	Improved schedule reliability, better resource use	Requires accurate baseline schedules	Suitable for complex and time-sensitive projects
Safety management	AI-enabled monitoring using vision systems and sensors	Improved hazard detection, enhanced safety compliance	Privacy and infrastructure concerns	Highly relevant; pilot use recommended for high-risk sites
Resource optimisation	AI analysis of labour, material, and equipment usage	Reduced waste, improved productivity	Data integration challenges	Applicable in phases, starting with material tracking
Predictive maintenance & O&M	AI-supported fault prediction for plant and services	Reduced downtime, extended asset life	Requires sensors and skilled personnel	Suitable for hospitals, commercial buildings, infrastructure
Change & variation management	AI-enabled BIM-based change tracking and version control	Improved traceability, faster approvals	Depends on BIM maturity	Highly relevant to public-sector projects with frequent variations

Despite its proven potential, AI and BIM adoption in Sri Lanka remains in the early stages. Major challenges include high initial investment costs, limited technical expertise, resistance to organizational change, fragmented data practices, and uneven digital readiness across the industry. Furthermore, traditional procurement methods and contract administration practices, especially in the public sector, hinder rapid digital transformation.

Nevertheless, significant opportunities exist. National digitalization initiatives and the National Artificial Intelligence Strategy (CFSAI, 2023) provide an enabling policy framework through skills development programmes, investment in digital

infrastructure, and support for public-private innovation. These initiatives lay the foundation for the gradual, structured integration of AI into construction contract management and post-contract administration.

A phased adoption approach is well-suited for Sri Lanka. Early efforts should focus on data standardization, document management, and basic BIM integration, then progress to advanced features like predictive analytics, automated progress monitoring, and AI-driven risk management. Pilot projects, especially in large public-sector and donor-funded projects, can showcase benefits, build institutional confidence, and promote broader industry adoption.



Figure 1: AI-enabled post-contract management and discipline-specific applications in Sri Lanka’s construction industry

Professional institutions, regulatory authorities, and academic organizations also play a critical role in promoting awareness, developing guidelines, and facilitating capacity building. By aligning industry practices with national digital strategies and professional standards, Sri Lanka can progressively embed AI into post-contract management processes in a sustainable manner.

8. Conclusion

AI is transforming how construction contracts are managed and how post-contract work is carried out. By automating documentation, improving coordination, and providing predictive insights, AI enhances the roles of project managers, engineers, and architects in the construction field. Each engineering discipline, including civil, electrical, mechanical, HVAC, architectural, and IT, particularly benefits from AI-driven tools.

AI presents both challenges and opportunities for Sri Lanka. While adoption remains limited, embracing AI in stages, beginning with data management, BIM integration, and risk monitoring, will deliver substantial benefits in productivity, transparency, and cost efficiency. Leveraging the National AI Strategy and building local capacity are essential for scaling AI adoption.

The future of AI in contract management emphasizes combining human expertise with machine intelligence. When properly integrated, AI will not replace professionals but will empower them to enhance construction project quality and accountability. With the right planning, investment, and professional involvement, AI can significantly improve the performance and competitiveness of Sri Lanka’s construction industry.

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Leveraging Building Information Modelling to Enhance Client Engagement and Project Delivery in the Sri Lankan Construction Industry

Best Article Section 2

Eng. Krishan Senadeera

Abstract Building Information Modelling (BIM) offers transformative potential for the Sri Lankan construction industry, which contributes approximately 7–8% to national GDP and is currently experiencing 8.5% year-on-year growth. This paper evaluates BIM implementation within the Sri Lankan context, examining its multi-dimensional capabilities (3D–7D) to enhance client engagement and improve project delivery outcomes. Key industry challenges including cost overruns, coordination failures, and inaccurate quantity take-offs are addressed through BIM’s enhanced visualization and real-time information sharing. BIM-based quantity take-offs achieve 95–98% accuracy compared to 85–90% with manual methods [4]. While BIM adoption remains nascent, local case studies from Altair, Colombo Port City and City of Dreams demonstrate achievable benefits. Barriers to adoption include high implementation costs, skills shortages, absence of national standards, contractual uncertainties, and limited government policy support. The paper concludes with coordinated strategic recommendations for government, professional bodies, and industry practitioners.

Keywords: *Building Information Modelling, Construction Technology, Client Engagement, Project Delivery, Cost Optimization, Sri Lankan Construction Industry*

1.0 Introduction and Contextual Analysis

The Sri Lankan construction industry operates within a complex economic and technical environment. Following the severe economic contraction of 2022 and 2023, the sector is experiencing a phase of stabilization and recovery, contributing approximately 7–8% to national GDP [1]. GDP contribution from construction reached LKR 253,273 million in Q3 2025, with year-on-year growth of 8.5% and first-half growth of 9.6% [1]. The Purchasing Managers’ Index for construction reached 67.6 in September 2025, the strongest reading since late 2021 [1].

Despite this recovery, Sri Lankan construction firms rely heavily on conventional project delivery methods, resulting in inefficiencies, quality issues, and reduced regional competitiveness. This paper evaluates Building Information Modelling (BIM) as a mechanism to improve project delivery, cost control, and client engagement.

Objective: To evaluate BIM implementation within the Sri Lankan construction context, identify implementation barriers and recommend a coordinated adoption strategy aligned with the local economic and professional landscape.

1.1 Technical Definition of Building Information Modelling

The National BIM Standard Project Committee defines BIM as “a digital representation of physical and functional characteristics of a facility that serves as a shared knowledge resource for facility information throughout its lifecycle from conceptual design to demolition” [5]. Unlike traditional CAD, BIM generates intelligent three-dimensional parametric objects whose changes automatically propagate to all associated views, eliminating coordination errors prevalent in manual workflows.

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1.2 BIM Maturity Levels and Industry Positioning

BIM has evolved through four maturity levels:

- Level 0: Traditional 2D CAD, no collaboration
- Level 1: 2D/3D CAD with limited file sharing
- Level 2: Collaborative 3D models per discipline, coordinated through a common data environment
- Level 3: Full collaboration on a single shared model

Most Sri Lankan firms operate at Level 0 or early Level 1. The United Kingdom and Singapore mandated Level 2 BIM for public projects by 2016 [2], representing a strategic gap and leapfrog opportunity for Sri Lanka.

1.3 Problem Statement: Limitations of Traditional Methodologies

Information Fragmentation

Architectural, structural, and MEP designs are developed in isolation in standard Sri Lankan practice, with coordination validated by error-prone manual visual checks. In high-rise buildings, this routinely produces costly clashes between structural and MEP elements.

Cost and Quantity Variance

Manual Quantity Take-Off (QTO) methods typical in Sri Lanka achieve 85–90% accuracy against actuals. BIM-based QTO achieves 95–98% accuracy through mathematical computation of model geometry [4]. In a volatile economic environment, even a 5–10% quantity variance significantly impacts contractor margins or causes client cost overruns.

Visualization and Client Communication

Clients frequently lack the technical training to interpret 2D orthographic projections, causing misunderstandings that result in costly late-stage change orders. BIM's intuitive 3D visualization eliminates this gap by enabling clients to understand the spatial reality before construction commences.

2.0 BIM Dimensions and Capabilities

Modern BIM implementations incorporate multiple dimensions, each adding specific value to project delivery and client engagement.

2.1 3D BIM: Geometric Visualization

Three-dimensional BIM provides geometric visualization enabling all stakeholders including non-technical clients to understand spatial relationships, aesthetic qualities, and functional layouts, reducing misinterpretation and enabling early identification of design issues.

2.2 4D BIM: Time Integration

4D BIM links model components to project schedules, enabling contractors to simulate the construction process, identify logistical challenges, optimize resource allocation, and communicate phasing and temporary works requirements to clients more effectively than traditional Gantt charts.

2.3 5D BIM: Cost Integration

5D BIM adds cost data, enabling real-time estimation, automated quantity take-offs, and budget tracking. Studies confirm 95–98% QTO accuracy versus 85–90% for manual methods [4], directly improving tender pricing accuracy and reducing contingencies particularly valuable in Sri Lanka's volatile economic environment.

2.4 6D BIM: Sustainability Analysis

6D BIM integrates energy and sustainability analysis tools, enabling designers to evaluate thermal performance, daylighting, and renewable energy potential before construction increasingly relevant as Sri Lanka pursues sustainable development goals.

2.5 7D BIM: Facility Management

7D BIM extends to facility management, serving as a digital twin containing equipment specifications, warranty periods, maintenance schedules, and spare parts information particularly valuable for complex MEP-intensive buildings where lifecycle maintenance costs can exceed initial construction costs.

3.0 Benefits of BIM Implementation

3.1 Cost and Time Benefits

McGraw Hill Construction [4] reports that 52% of BIM-using firms experienced reduced project duration and 49% reported improved project margins. Bryde et al. documented positive outcomes in cost reduction (35% of cases), time savings (25% of cases), and improved stakeholder communication (60% of cases). These benefits derive primarily from clash detection resolving design conflicts before construction.

3.2 Enhanced Client Engagement

BIM visualization augmented by virtual and augmented reality enables immersive client experiences, reducing design changes during construction. Research indicates that BIM-enabled projects experience fewer change orders and higher client satisfaction ratings.

3.3 Improved Coordination and Clash Detection

Automated clash detection analyses the integrated model to identify geometric conflicts between disciplines. Case studies indicate that effective clash detection reduces coordination-related rework by 50–70%, translating to significant cost savings and schedule improvements.

3.4 Sri Lankan Case Study Evidence

Several high-profile Sri Lankan projects demonstrate BIM's local applicability. The Altair residential tower utilized BIM for complex façade coordination. Colombo Port City employs BIM across disciplines to coordinate extensive underground utilities and superstructure elements. Access Engineering implemented BIM for the City of Dreams integrated resort, achieving improved quantity accuracy and reduced coordination issues [6]. Research on high-end residential projects during the 2020–2023 economic crisis documented improved cost control, schedule adherence, and client satisfaction in BIM-enabled projects compared to conventional delivery [6].

4.0 Implementation Challenges in Sri Lankan Context

4.1 High Initial Investment Costs

Major BIM platform licenses (Autodesk Revit, Graphisoft ArchiCAD, Bentley Systems) typically cost USD 2,000–5,000 per user annually [3], prohibitive for many small and medium Sri Lankan enterprises. Additional high-performance hardware requirements further increase capital requirements.

4.2 Skills Shortage and Training Gaps

Sri Lankan universities have only recently begun incorporating BIM into curricula, meaning most practicing professionals lack formal BIM training. Short-term courses often focus on software operation rather than comprehensive BIM methodology. Experienced BIM coordinators and managers are scarce, constraining adoption.

4.3 Absence of Standards and Guidelines

Sri Lanka currently lacks national BIM standards, creating uncertainty about implementation requirements, file formats, naming conventions, and information delivery. Without standardized approaches, each project team must independently develop these guidelines, reducing efficiency and interoperability.

4.4 Contractual and Legal Uncertainties

Traditional contracts based on 2D drawings do not adequately address BIM-specific issues such as model ownership, permitted uses, data accuracy liability, and coordination responsibilities. These ambiguities create reluctance among clients and contractors to fully embrace BIM workflows.

4.5 Cultural Resistance and Change Management

Established workflows and fear of technology create organizational resistance. Successful BIM adoption requires not only technical training but also change management, new workflow establishment, and senior management commitment to drive cultural transformation.

4.6 Limited Government Support and Policy Framework

Unlike developed nations where government mandates have accelerated BIM adoption, Sri Lanka's Construction Industry Development Authority (CIDA) has not yet mandated BIM for public sector projects, removing a primary market driver that has proven effective internationally.

5.0 Recommendations for Successful BIM Adoption

5.1 Phased Implementation Strategy

Firms should begin with 3D visualization and progress to advanced capabilities as organizational maturity develops:

1. Phase 1: 3D visualization for design development and client communication
2. Phase 2: Automated QTO for cost estimation and tendering
3. Phase 3: Multi-discipline coordination and clash detection
4. Phase 4: 4D construction sequencing and site planning
5. Phase 5: 7D facility management and lifecycle asset information

5.2 Comprehensive Training and Capacity Building

The IESL, IIESL and Institute of Quantity Surveyors Sri Lanka should develop BIM training programmed addressing methodology, collaborative workflows, and project management not only software operation. Universities should integrate BIM into architecture, engineering, and quantity surveying curricula. Certification programmes aligned with building SMART international standards should establish professional development pathways.

5.3 Development of National BIM Standards

Sri Lanka should develop national BIM standards adapted from ISO 19650 [5] and established international frameworks, covering model development requirements, information exchange

protocols, file formats, naming conventions and coordinate systems. CIDA should coordinate this multi-stakeholder standards development process.

5.4 Government Policy Support and Incentives

A phased mandate beginning with public building projects exceeding LKR 500 million, complemented by tax deductions for BIM software investment, subsidized training, and preferential tender evaluation criteria for BIM-capable firms, would create both supply-side and demand-side drivers for adoption. The 2025 national budget's emphasis on digitalization provides a favorable policy environment.

5.5 Pilot Projects and Knowledge Sharing

Industry associations should facilitate pilot projects across building types (residential, commercial, infrastructure) and establish a BIM community of practice for ongoing knowledge exchange, case study documentation, and peer support.

6.0 Conclusions

BIM's multi-dimensional capabilities address Sri Lanka's persistent construction challenges coordination failures, cost overruns, and limited client engagement. The industry's current economic recovery (8.5% year-on-year growth [1]) creates an opportune window for technology adoption. BIM-based QTO accuracy of 95–98% versus 85–90% for manual methods [4] is particularly valuable in Sri Lanka's volatile economic context.

Current adoption is primarily limited to large firms and high-end projects. Key barriers are high costs, skills shortages, absence of national standards, contractual uncertainties, and insufficient government policy support. Local case studies (Altair, Colombo Port City, City of Dreams) validate BIM's applicability to Sri Lankan conditions.

Successful adoption requires phased implementation, comprehensive training, national standards development, government policy mandates and coordinated multi-stakeholder engagement. As regional competition intensifies, BIM transitions from an optional enhancement to an essential capability for industry competitiveness.

7.0 Acknowledgement

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Influence of Emotional Intelligence for Successful Construction Project Management

Eng. S.A. Jabbar

Abstract; in construction projects, success is usually measured by cost, quality, and time. But in reality, technical knowledge alone is not enough to complete projects on schedule or satisfy everyone involved. This paper discusses how Emotional Quotient (EQ), also known as Emotional Intelligence (EI), helps project managers achieve their goals on time. Emotional intelligence includes understanding and managing one's own emotions, staying motivated, showing empathy toward others, and building good relationships. These abilities help project team leaders reduce stress, solve problems peacefully, and encourage teamwork in difficult situations.

The paper shows that emotionally intelligent leaders communicate better, gain trust, and manage cultural or personal differences among team members. It also explains that emotional intelligence can be learned and improved through practice, self-reflection, and training. When emotional intelligence is used together with technical skills, it makes project management more effective and flexible. This helps reduce delays and improves project results.

The lessons presented are derived from practical experience with private contractors involved in the rehabilitation and reconstruction of irrigation headworks and conveyance systems, as well as community-driven development projects implemented by government institutions and international agencies, including the Food and Agriculture Organization of the United Nations (FAO-UN) and the Japan International Cooperation Agency (JICA). Particular emphasis is placed on attitudinal and behavioral change as a critical approach to addressing contextual challenges and enhancing project management effectiveness and outcomes. Within this framework, Emotional Intelligence (EI) is identified as an essential competency for contemporary construction managers, supporting timely project delivery and effective collaboration among all stakeholders.

Keywords: Emotional Intelligence, Construction Project Management, Leadership, Teamwork, Communication.

Introduction

It is a well-established fact that project success is often measured through technical and financial performance. However, there exists a less visible but equally critical factor that contributes to the successful completion of projects—Emotional Quotient (EQ) or Emotional Intelligence (EI). A manager with a high Intelligence Quotient (IQ) alone may not be able to ensure project success unless complemented by a high degree of emotional intelligence.

Project management can be defined as the process of achieving objectives by effectively utilizing labour, machinery, equipment, and other resources. In a construction project, multidisciplinary professionals and workforces, work together toward a common goal. To ensure smooth coordination and productive performance from this diverse team, the project manager must possess a positive attitude and the ability to motivate and harmonize individuals. This positive attitude acts as a catalyst for developing and applying emotional intelligence in management practice.

Traditionally, IQ has been viewed as a measure of memory capacity and analytical ability. More recent perspectives, however, also recognize it as reflecting an individual's ability to accept and adapt to change.

IQ is largely innate and varies from person to person. In contrast, Emotional Intelligence (EI) can be developed and strengthened over time through conscious practice, empathy, self-regulation and positive interpersonal engagement.

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In construction projects of any type, a manager possessing high intellectual capacity but limited emotional intelligence is likely to encounter challenges in leading projects smoothly and achieving the intended outcomes. Effective project management requires not only technical and analytical competence but also emotional awareness, empathy, and interpersonal sensitivity. These observations are consistently supported by practical experience and lessons learned from projects implemented by government institutions and international agencies, including the Japan International Cooperation Agency (JICA) and the Food and Agriculture Organization of the United Nations (FAO-UN).

Objectives:

- To investigate the influence of Emotional Intelligence on successful Construction Project Management.
- To highlight important of the Emotional Intelligence in shaping the attitudes and behaviors of Construction Project Managers for successful project completion.
- To provide practical-based evidence of the impact of Emotional Intelligence on successful project outcomes.

2.0 Construction Project Management – Technical Practices and the Role of Emotional Quotient/Intelligent

Construction management plays a pivotal role in the overall process of project implementation. A construction project is not merely the act of building a physical structure but the culmination of a series of systematic and interrelated phases that translate conceptual ideas into tangible outcomes. Typically, the project life cycle involves preliminary studies, detailed investigations, design development, preparation of architectural and structural drawings, procurement, and finally, construction and commissioning. Each of these stages demands precision, coordination, and effective decision-making from both technical and managerial personnel.

The final phase—construction—is where ideas and designs materialize into physical form. This stage transforms technical drawings into a real structure, bringing together diverse resources such as materials, machinery, finances and most

importantly, human skills. The Project Manager serves as the central figure responsible for harmonizing these resources and ensuring the seamless execution of the project according to planned specifications, timelines and budgets.

However, it is important to recognize that successful project delivery requires more than technical proficiency **alone** or the availability of material resources. The process is inherently complex and often accompanied by challenges such as stress, pressure, fatigue, and interpersonal conflicts among team members. Navigating these conditions demands a strong Emotional Quotient (EQ)—the capacity to remain composed, empathetic, and solution-oriented under demanding circumstances. Accordingly, patience, resilience, and emotional balance are essential attributes of effective construction management.

A successful construction project rely on effective collaboration among multi-disciplinary teams, including technical, administrative and operation personnel. Each member brings unique expertise, background, and mindset, resulting in a wide spectrum of Intelligence Quotient (IQ) and Emotional Quotient (EQ) levels. While IQ determines analytical and problem-solving capabilities, EQ governs interpersonal relations, teamwork, and adaptability. A Project Manager’s role thus extends beyond supervision to leadership, motivation, and emotional guidance — creating a cohesive and motivated team environment despite varying personalities and stressors.

Importantly, while IQ is largely innate, EQ can be nurtured and developed. Structured training programs, emotional intelligence workshops, leadership coaching, and communication skill development are effective means to strengthen EQ among professionals in the construction industry. When managers and team members learn to recognize their emotions, regulate reactions, empathize with others, and maintain a positive attitude, they enhance their capacity to work cooperatively and handle conflicts constructively.

In practice, construction management is far more than organizing materials or scheduling tasks—it is about managing people and emotions within complex and changing environments. The technical side of project management provides the framework, but it is the human side—grounded in emotional intelligence—that sustains progress when challenges arise.

Construction project implementation is a multifaceted process that requires a careful balance between technical efficiency and emotional maturity. While adequate resources, appropriate technology, and sound planning form the structural

foundation of a project, it is mutual understanding, empathy, emotional control, kindness, and a positive attitude that sustain progress and ensure successful completion in community-participatory settings. The effectiveness of a project manager, therefore, depends not only on technical expertise or analytical ability but also on the capacity to inspire, motivate, and meaningfully engage with contractors, community members and stakeholders. In this context, Emotional Intelligence emerges as a silent yet powerful force driving excellence in construction project management.

2.10 Emotions and Emotional Quotient (EQ) / Emotional Intelligence (EI)

2.1.1 Emotions

Emotions form the foundation of human behavior and are an integral part of psychological and social life. They influence how individuals think, make decisions, communicate, and act in different situations. In organizational contexts, emotions have a significant impact on motivation, teamwork, leadership, and overall performance. The ability to recognize and manage emotions—both one's own and those of others—is essential for maintaining harmony, productivity, and effective professional relationships.

Emotions are natural and meaningful responses to life experiences, arising from interactions with the environment and with other people. Expressions such as crying in sorrow, laughing in happiness, showing anger, or feeling frustration in the face of challenges are instinctive reactions. These responses demonstrate how closely emotions are linked to human existence, enabling individuals to process experiences, communicate needs, and adapt to changing circumstances.

Psychologists and behavioral experts commonly identify eight primary categories of emotions that give rise to more complex emotional states:

- **Joy** – A sense of happiness or contentment that reinforces positive behavior and strengthens relationships.
- **Anger** – A response to perceived injustice or frustration which, when managed effectively, can motivate constructive change.
- **Trust** – The basis of cooperation and effective communication, essential for building confidence within teams and organizations.
- **Surprise** – A reaction to unexpected events that prompts rapid reassessment of situations.
- **Anticipation** – A forward-looking emotion that supports planning, motivation, and preparedness.

- **Fear** – A protective response to potential threats or risks that encourages caution and preparedness when properly controlled.
- **Disgust** – A reaction to unpleasant or unethical stimuli that helps preserve moral and physical well-being.
- **Sadness** – An emotional response to loss or disappointment that encourages reflection and empathy.

Emotions are not merely reactions but essential tools for survival and success. They guide social interaction, moral judgment, and adaptation to change. In professional settings, emotions directly influence leadership effectiveness, teamwork, conflict resolution, and workplace morale. Individuals with strong emotional awareness are better able to understand others, manage stress, and foster trust and collaboration.

As often stated, emotion is not only important but necessary for sound decision-making, effective problem-solving, coping with change, and achieving success. In essence, emotions connect thought and action. When acknowledged and managed wisely, they become a source of strength, enhancing personal development, improving communication, and contributing to collective success in both personal and organizational contexts.

2.1.2 Emotional Quotient (EQ) or Emotional Intelligence (EI)

Emotional Intelligence (EI) did not receive substantial research attention until the release of Daniel Goleman's influential book *Emotional Intelligence (1995): Why It Can Matter More Than IQ*. Following its publication, the concept gained significant visibility across academic circles, the media, and the commercial sector.

Unlike IQ, which usually remains steady throughout life, EI can improve through learning, practice, and experience. Goleman's work drew wide attention because he suggested that EI can sometimes be more important than IQ and that it strongly influences success in many types of jobs.

Emotional intelligence is often defined as the ability to perceive emotions, reason with them, and use this understanding to guide thought and action. It consists of several interrelated dimensions that are particularly relevant in the construction sector:

1. **Self-Awareness** – Understanding one's emotions, strengths, and limitations, and how these affect decision-making and interactions on site.

2. **Self-Regulation** – Managing emotions under pressure, maintaining composure amid conflict, and demonstrating consistent professionalism.
3. **Motivation** – Maintaining focus, enthusiasm, and persistence even when facing schedule delays, budget constraints, or site challenges.
4. **Empathy** – Recognizing the emotions, concerns, and needs of workers, subcontractors, and clients, and responding with understanding and fairness.
5. **Social Skills** – Building trust, resolving disputes, influencing teams positively, and maintaining open communication channels.

2.1.3 Summary of Emotional Intelligence

- Emotional intelligence is distinct from, but positively related to, other intelligences.
- Emotional intelligence is an individual difference, where some people are more endowed, and others are less so.
- Emotional intelligence develops over a person's life span and can be enhanced through training.
- Emotional intelligence involves, at least in part, a person's abilities to identify and perceive emotion (in self and others), as well as the skills to understand and manage those emotions successfully.

Construction projects involve many professionals working together under pressure, uncertainty, and strict deadlines. In such environments, technical knowledge alone is not enough. Leaders with strong emotional intelligence are often better at managing people, solving problems, and guiding teams smoothly.

2.20 Emotional intelligence and construction project management:

The construction industry has been reported as significantly different from other industries, describe it as one of the most risky, complex and dynamic industrial environments and claim that it shows the potential to undermine the applicability of managerial tools and techniques proven successful in other sectors. The corollary thereof is that construction's specific characteristics require an individual approach, especially considering human resource management. Construction as a labor-intensive industry specifically relies on people.

Human resource costs account for a large share of total expenditure; therefore, improving and optimizing workforce effectiveness and performance can lead to substantial cost savings,

while also influencing important factors such as employee satisfaction, commitment, and well-being.

2.2.1 Construction Project Management Characteristics and Their Implications

Construction projects are usually unique and non-repetitive. Project managers must adapt their management approach to each situation. Projects are often awarded at short notice, which creates time pressure. This requires strong emotional control and quick decision-making.

The construction industry relies heavily on a temporary workforce. This can affect team unity, communication, and consistent performance. Emotional intelligence is therefore important for building trust and cooperation.

Client expectations are increasing. This places additional pressure on project teams. Managers must balance technical skills with strong interpersonal abilities. The industry is also traditionally male-dominated, which can influence leadership styles and workplace behavior. Emotionally intelligent leadership is essential for collaboration, conflict resolution, and overall project success.

2.2.2 Rationale for the Application of Emotional Intelligence in Construction

Emotional intelligence has been increasingly recognized as a critical competency for improving construction project performance. The construction industry has traditionally been characterized by an adversarial, blame-oriented, and conflict-prone culture, which undermines collaboration and project efficiency. Smyth (2004, pp. 44–53) argues that the development of behavioral and relational competencies, including emotional awareness and interpersonal skills, is essential to mitigating conflict and enhancing cooperative working relationships within construction projects.

As construction projects involve multiple stakeholders with differing objectives, emotional intelligence serves as an effective management tool for fostering collaboration, trust, and effective communication among project teams. The ability of project managers to understand, regulate, and respond appropriately to emotions contributes significantly to improved teamwork and coordinated decision-making, thereby positively influencing project outcomes.

Furthermore, emotional intelligence has been identified as a vital selection criterion for future

generations of construction project managers. Butler and Chinowsky (2006, pp. 121–124) demonstrate that emotionally intelligent construction executives exhibit more effective leadership behaviors, which are closely associated with enhanced organizational and project performance. Their findings also emphasize the importance of integrating emotional intelligence into leadership development and executive selection processes.

In addition, emotional intelligence is increasingly regarded as an intrinsically important element of engineering and construction education. Embedding EI within professional training frameworks enables the development of practitioners who can complement technical competence with leadership capability, ethical judgment, and performance-oriented interpersonal skills, thereby contributing to sustainable improvements in construction project delivery.

3.0 Methodology: Qualitative Multi-Case Research Framework

This study employed a qualitative, multi-case research design to examine the role of Emotional Intelligence (EI) in project performance within post-conflict, community-based rehabilitation programmes implemented in Sri Lanka between 2006 and 2019. The analysis draws on evidence from the TRINCAP project (supported by JICA) in Trincomalee District and FAO–UN–supported irrigated agricultural rehabilitation initiatives in the Northern and Eastern Provinces, enabling cross-case comparison across different institutional and operational contexts.

Data sources included direct field observations and professional experience during project implementation, field notes and diaries, Community Action Plans (CAPs), Participatory Rural Appraisal (PRA) outputs, consultation records, project reports, engineering documentation, and performance and completion records. Observations of interactions among engineers, field staff, community leaders, farmers, and implementing agencies provided additional insight into leadership behavior and team dynamics.

The analysis was guided by key EI dimensions—self-awareness, self-regulation, motivation, empathy, and social skills—which were used as interpretive lenses to assess observed behaviors of project leaders and staff. Project outcomes, including community participation, conflict reduction, trust building, acceptance of CAPs and timely completion of works, were examined to evaluate EI influence.

Field evidence was thematically analyzed across project stages from planning to handover, and findings were validated through triangulation of multiple data sources. Although EI was not measured quantitatively, its influence was assessed through observable behavioral indicators such as collaboration, dispute resolution, stakeholder engagement and community participation.

3.1 Emotional Intelligence Across Project Phases and Leadership

3.1.1 Leadership Validation

- a) Construction projects require the coordination of multiple teams, encompassing all levels from field workers to top management, often under demanding physical and time constraints. Leadership effectiveness in such contexts depends not only on technical competence but also on emotional awareness.

An emotionally intelligent project leader is able to assess team morale, recognize signs of fatigue or frustration, and intervene appropriately to sustain motivation. As Deputy Chief Advisor to the JICA-TRINCAP project, the author observed emotionally intelligent leadership demonstrated through empathy, clear communication, and adaptability. Such leadership, characterized by a clear articulation of a vision and empathetic engagement, fostered trust and cooperation among diverse groups of professionals and laborers. Consequently, this leadership approach enhanced team motivation, strengthened community confidence, and contributed to smoother and more efficient project implementation. Post-conflict construction projects implemented by the Food and Agriculture Organization of the United Nations (FAO) in Sri Lanka demonstrate the practical value of Emotional Intelligence (EI) in construction project management. Between 2010 and 2015, FAO rehabilitated 52 minor irrigation tanks in the Eastern Province and 72 in the Northern Province, completing all works within the planned schedules.

Although project funding was adequate, delays in interim payments occasionally occurred due to contractor non-compliance with technical specifications. These situations created operational pressure and the potential for disruption to site activities. In response, project leadership applied emotionally intelligent practices rather than relying solely on rigid contractual enforcement. Patience, clear

communication, and emotional diplomacy were used to address contractor concerns while ensuring corrective actions and compliance with required standards.

This approach helped reduce tensions, maintain constructive working relationships, and ensure continuity of works. The experience confirms that emotionally intelligent leadership complements technical expertise and is a critical factor in achieving successful outcomes in post-conflict construction environments.

3.1.2 Assessment of Project Activities across Different Phases

During the implementation of JICA–TRINCAP and FAO–UN irrigated agricultural projects in Northern and Eastern Sri Lanka, activities were monitored across all project phases. During needs assessment and Participatory Rural Appraisal (PRA), officers demonstrating empathy collected accurate, context-relevant information, producing Community Action Plans (CAPs) that were realistic, feasible and widely accepted by stakeholders.

In the planning and design phase, emotional control and social skills facilitated fair negotiation of design issues, minimizing conflicts and ensuring equitable, sustainable solutions. During implementation, motivated and emotionally balanced teams contributed to timely and successful project completion.

Across both projects, findings show that while technical expertise is essential, Emotional Intelligence (EI) is a critical factor influencing stakeholder cooperation, conflict management, and project continuity. From assessment to handover, EI consistently enhanced project performance, confirming its central role in post-conflict, community-based rehabilitation initiatives.

3.1.3 Emotional Intelligence as a Driver of Timely Delivery

Evidence from the implementation of JICA–TRINCAP and FAO–UN agricultural projects shows that timely project delivery depends on both accurate planning and emotional stability. Emotional Intelligence (EI) supports effective time management by improving communication, reducing misunderstandings, and fostering accountability among project teams.

Project managers who demonstrated empathy encouraged team members to perform beyond expectations. The successful and timely completion of both projects was largely due to technical staff who managed stress calmly and consistently. Their composure influenced the wider workforce, enabling steady productivity and efficient performance under tight deadlines.

Overall, EI acted as an invisible force that integrated technical coordination, team motivation, and on-time project delivery, highlighting its essential role in achieving project objectives.

4.0 Conclusion

This study demonstrates that Emotional Intelligence (EI) plays a decisive role in the successful management of construction projects, particularly in post-conflict and community-based rehabilitation contexts. Evidence from the JICA–TRINCAP and FAO–UN–supported projects in Sri Lanka confirms that while technical expertise is essential, it is insufficient on its own to address the social, institutional, and operational complexities of such environments.

Across all project phases, EI consistently influenced leadership effectiveness, stakeholder cooperation, and project continuity. Leaders who exhibited empathy, emotional control, and strong social skills were better able to manage team dynamics, resolve conflicts, and maintain trust among contractors, field staff, and communities. EI-enabled practices proved especially valuable during periods of stress, technical non-compliance, and tight schedules, where calm communication and emotional diplomacy prevented escalation and supported corrective action.

The findings also show that EI contributed directly to timely project delivery by improving communication, reducing misunderstandings and sustaining workforce motivation. In post-conflict settings, where projects are exposed to uncertainty and heightened sensitivities, EI functioned as a stabilizing force that aligned technical coordination with human behavior.

Overall, the study confirms EI as a critical managerial competency in construction project management. Integrating EI development into leadership training and professional practice can significantly enhance project performance, stakeholder satisfaction and the long-term sustainability of construction outcomes.

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