

Leveraging Digital Innovations for Lean and Sustainable MEP in the Industry 4.0 Era

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Abstract

Mechanical, Electrical, and Plumbing (MEP) systems construction is one of the most resource-intensive and coordination-critical components of building projects. However, many digital transformation efforts in construction remain fragmented, technology-driven, and weakly connected to process improvement and sustainability outcomes. This study addresses this gap by developing an Industry 4.0-enabled Lean-Green framework that explicitly links digital technologies to MEP process optimisation and environmental performance. Rather than viewing Industry 4.0 tools as isolated solutions, the research examines how key digital technologies—Building Information Modelling (BIM), Industrial Internet of Things (IIoT), Digital Twins, and Artificial Intelligence (AI)—interact with Lean principles such as flow stabilisation, waste elimination, and right-first-time execution, and how they relate to Green construction objectives including energy efficiency, material optimisation, and carbon reduction. The study adopts a structured methodology combining systematic literature synthesis, technology-process mapping, industrial benchmarking, pilot case study integration, and design science-based framework development to identify where digital technologies create measurable Lean-Green synergies across MEP workflows. The primary contribution is a tri-layer Industry 4.0-enabled Lean-Green framework (I4LGF-MEP) consisting of: (1) a Lean process optimisation layer, (2) a Green sustainability performance layer reflecting environmental impacts, and (3) a digital intelligence layer supported by cyber-physical feedback loops. At the centre of the framework is a Cyber-Physical Lean-Green Loop (CPLGL), where real-time data from MEP activities is used to continuously evaluate and improve both process efficiency and environmental performance. The findings indicate that digitalisation delivers value only when technologies are clearly aligned with Lean mechanisms and sustainability metrics, providing a structured foundation for advancing Lean and sustainable MEP construction.

Keywords

Industry 4.0, Lean Construction, Green Construction, MEP Systems, Cyber-Physical Systems, Digital Twins

1. Introduction

Mechanical, Electrical, and Plumbing (MEP) systems represent some of the most complex and resource-intensive components of modern construction projects. These systems account for a substantial portion of project cost, embodied carbon, and operational energy consumption, yet they remain among the least digitally integrated elements of the built environment. Despite significant advances in construction technology, MEP installation continues to be characterised

by fragmented workflows, high levels of rework, coordination failures, and inadequate integration between process improvement initiatives and sustainability objectives.

The construction industry's response to these challenges has primarily taken one of two forms: the adoption of Lean construction principles to eliminate waste and improve workflow, or the deployment of Industry 4.0 technologies to enhance visibility and data-driven decision-making. While both approaches offer partial improvements, they are seldom implemented in a coordinated and unified manner. More critically, neither approach has been systematically aligned with the environmental performance requirements that now define sustainable construction practice. The result is a persistent three-way fragmentation between Lean process management, sustainability assessment, and digital technology implementation, a gap that this research directly addresses.

The motivation for this study stems from the recognition that MEP construction in an Industry 4.0 context requires a fundamentally different approach—one that treats process efficiency, environmental performance, and digital intelligence not as separate initiatives but as interdependent dimensions of a unified operational system. A pilot case study conducted in a power plant process piping installation context provides empirical grounding: across 1,450 observed man-hours over a 33-day period, only 9% of total effort was classified as value-adding, while 68% constituted non-value-adding waste and 23% necessary support activities. This level of inefficiency is not incidental; it reflects structural process deficiencies that simultaneously drive environmental burden and constrain digital integration.

This study aims to develop an Industry 4.0-enabled Lean-Green integrated framework for MEP construction systems (I4LGF-MEP) that explicitly aligns digital technologies with Lean principles and Green sustainability metrics within a unified cyber-physical operational architecture. Specifically, the study: (i) establishes the tri-layer conceptual architecture of the I4LGF-MEP framework; (ii) develops and characterises the Cyber-Physical Lean-Green Loop (CPLGL) as the central feedback and optimisation mechanism; (iii) operationalises sustainability assessment through Environmental Value Stream Mapping 4.0 (E-VSM 4.0); (iv) defines an Industry 4.0 readiness and maturity model applicable to MEP activities; and (v) validates the framework's conceptual foundations through industrial benchmarking and a pilot case study in a power plant piping environment.

2. Literature Review

Lean construction has evolved significantly since its foundational articulation by Koskela (2000), who argued that construction should be conceptualised as a flow-based production system rather than a transformation process alone. The principles of waste elimination, takt-based flow control, pull planning, and right-first-time execution have since been applied across numerous construction sectors. However, their application to MEP systems has remained comparatively underdeveloped, with limited attention to the specific flow interruptions, coordination dependencies, and waste patterns that characterise MEP installation environments (Sacks et al. 2020; Dave et al. 2021).

Sustainability in construction has been addressed through a range of frameworks and assessment tools, including Life Cycle Assessment (LCA), green building rating systems such as BREEAM and LEED, and Environmental Value Stream Mapping (E-VSM). While these tools provide a basis for measuring environmental performance, they are predominantly project-level, post-hoc instruments that do not integrate with operational workflows in real time (Durdyev and Hosseini 2020; Tsao et al. 2021). The absence of process-embedded sustainability monitoring means that environmental improvements are rarely achieved through operational optimisation; rather, they depend on design-stage decisions that may be significantly diluted during construction execution.

Industry 4.0 technologies have attracted substantial research attention in the construction domain, particularly Building Information Modelling (BIM), Industrial Internet of Things (IIoT), Digital Twins, and Artificial Intelligence (AI). BIM has demonstrated strong potential for coordination improvement and clash detection (Azhar 2011; Sacks et al. 2018), while IIoT technologies support real-time monitoring of site conditions, equipment performance, and material flows (Ding et al. 2018; Pan and Zhang 2021). Digital Twins enable simulation-based optimisation and predictive performance modelling (Grieves and Vickers 2017; Lu et al. 2020), and AI-based systems have shown capability in schedule prediction, resource allocation, and defect detection (Xu et al. 2021; Fang et al. 2020).

However, a consistent finding across this body of literature is that these technologies are deployed in isolation, addressing specific functional domains such as design coordination or progress monitoring, without systematic integration into production control systems or sustainability evaluation frameworks. Several recent systematic reviews

have confirmed this fragmentation. Ajayi et al. (2022) found that digital construction research lacks explicit linkages between technology deployment and measurable sustainability outcomes. Similarly, Oesterreich and Teuteberg (2016) demonstrated that Industry 4.0 adoption in construction remains predominantly tool-centric rather than system-centric, with limited interoperability between digital platforms, site operations, and performance management.

The emerging concept of Lean Construction 4.0 represents an attempt to address this fragmentation by combining Lean principles with digital enablement (Haghshenas et al. 2021; Yin et al. 2022). However, existing Lean 4.0 frameworks remain largely manufacturing-oriented, with limited adaptation to the project-based, variable, and spatially complex nature of MEP construction. Furthermore, Green dimensions are rarely incorporated as a structural framework component; environmental considerations are treated as secondary outcomes of efficiency improvement rather than as co-equal performance objectives.

The concept of cyber-physical systems (CPS) in construction has been explored by Lee et al. (2015) and Lasi et al. (2014) in the context of Industry 4.0 architectures, demonstrating that closed-loop feedback integration between physical operations and digital intelligence systems can significantly enhance process stability and adaptive optimisation capability. Nevertheless, no existing framework applies CPS principles to MEP construction with an explicit integration of Lean process logic and Green sustainability performance, confirming the research gap that motivates this study.

Industrial benchmarking from advanced manufacturing provides additional theoretical grounding. Toyota's Production System (TPS), Siemens' digital factory at Amberg, Bosch's Lean 4.0 implementation, and Volkswagen Autoeuropa's digital transformation all demonstrate that Industry 4.0 technologies deliver maximum value when they serve as enablers of Lean operational principles rather than as replacements for structured process management (Liker 2020; Siemens 2025; Bosch 2023). These manufacturing cases validate the conceptual direction of the proposed framework while highlighting the need to adapt their principles to the dynamic and less controllable conditions of construction environments.

In summary, the literature confirms that a three-way integration of Lean construction principles, environmental sustainability metrics, and Industry 4.0 digital technologies within a cyber-physical framework represents both a significant research gap and an emerging priority for the MEP construction sector. The present study addresses this gap through the development and characterisation of the I4LGF-MEP framework.

3. Methods

The research methodology is grounded in Design Science Research (DSR) as articulated by Hevner et al. (2004), combined with Systems Thinking principles following Sterman (2000). DSR was selected because the study aims not merely to analyse existing relationships between Lean, sustainability, and Industry 4.0 technologies, but to design, construct, and validate a novel operational framework capable of addressing complex interactions within MEP construction systems. Systems Thinking enables the research to address the interconnected, dynamic, and feedback-driven nature of these interactions, which resist reduction to single-variable causal models.

The methodology progresses through six integrated stages. The Synthesis Stage consolidates theoretical relationships identified through systematic literature review, translating Lean principles, sustainability objectives, and Industry 4.0 technologies into interconnected conceptual blocks. The Modelling Stage converts these relationships into a systems-based framework using System Dynamics and functional architecture mapping to represent feedback loops and cyber-physical interactions across MEP workflows. The Industrial Benchmarking Stage examines how advanced manufacturing systems—Siemens, Bosch, Toyota, and Volkswagen—have integrated Lean, digital, and sustainability practices, extracting transferable principles relevant to MEP construction. The Pilot Case Study Integration Stage utilises a previously documented power plant process piping project to provide empirical grounding, where observed Lean deficiencies serve as the operational basis for Green and Industry 4.0 layer integration. The Literature-Based Validation Stage cross-references each framework component against identified research gaps to ensure that the proposed model constitutes a direct and justified response to documented limitations. Finally, a planned Refinement Stage will employ the Delphi Method to achieve expert consensus on framework feasibility and practical applicability. Data collection for the pilot case study was conducted over 33 working days at an auxiliary boiler facility in Qatar, involving continuous video observation of two installation crews. Every distinct action was logged, timed, and classified using a three-category Lean taxonomy: Value-Adding (VA), Non-Value-Adding (NVA), and Non-Value-Adding but Required (NVAR). The resulting dataset of approximately 1,450 man-hours constitutes the empirical

baseline for the Lean layer of the framework, against which Green metrics and Industry 4.0 enablers are subsequently mapped.

4. Framework Architecture and Development

The I4LGF–MEP framework is structured as a tri-layer architecture that systematically integrates Lean process optimisation, environmental sustainability, and Industry 4.0 digital technologies into a unified operational model. The three layers are not sequential or hierarchical in a prescriptive sense; rather, they are interacting dimensions of a single cyber-physical system (Figure 1).

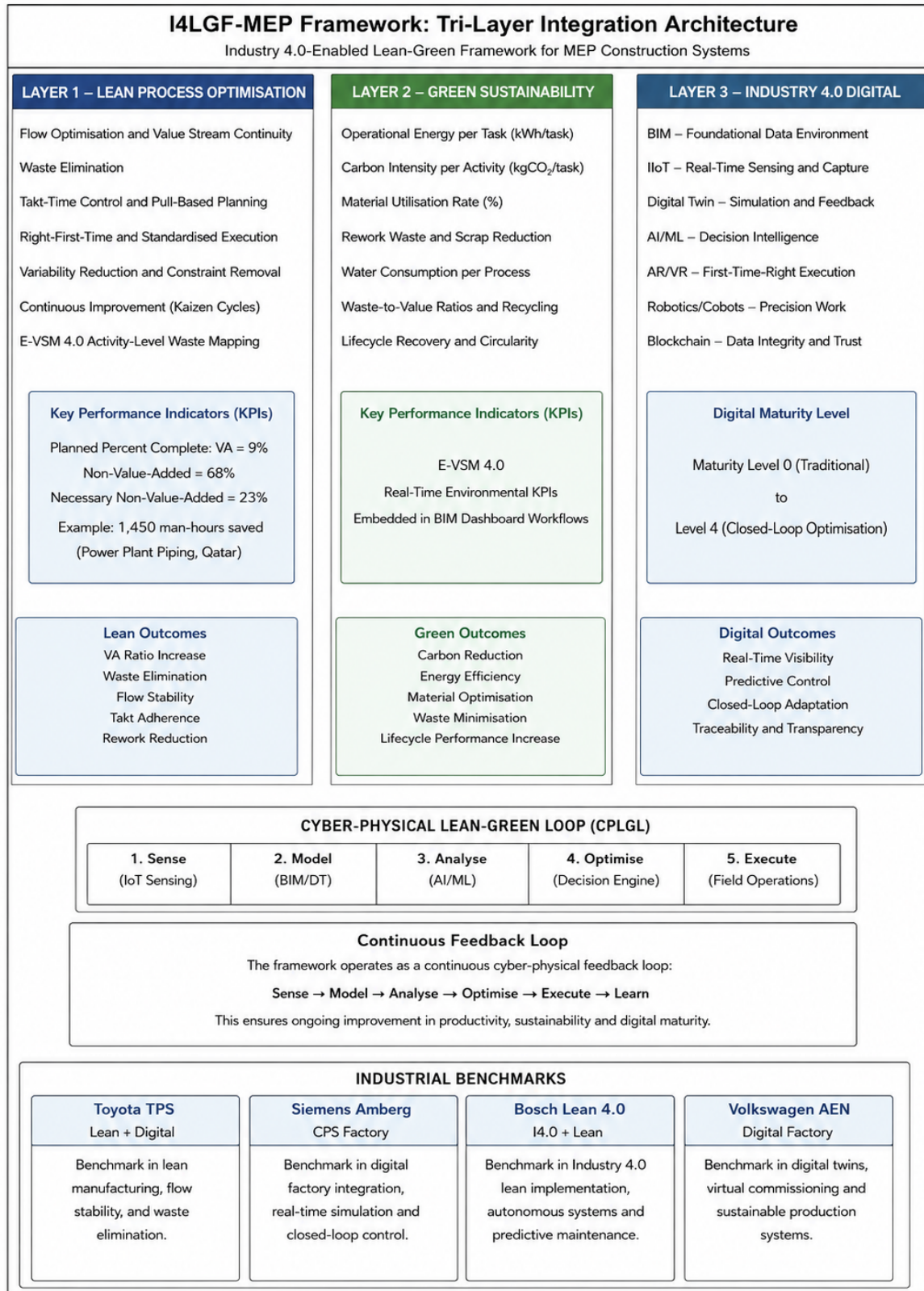


Figure 1. The I4LGF–MEP Tri-Layer Integration Framework showing the Lean Process Optimisation Layer, Green Sustainability Layer, Industry 4.0 Digital Layer, and the governing Cyber-Physical Lean–Green Loop (CPLGL).

4.1 Tri-Layer Architecture

The Lean Layer forms the operational foundation of the framework. It is grounded in measurable, technology-enabled Lean principles: flow optimisation and value stream continuity; elimination of the seven waste types (transport, waiting, motion, overprocessing, defects, overproduction, and unused talent); variability reduction and takt-time control; pull-based coordination and constraint removal; standardisation and first-time-right execution; and continuous improvement enabled through real-time feedback. Broader Lean dimensions such as organisational culture and leadership behaviour are intentionally excluded from this layer because they are not directly quantifiable through digital technologies and fall outside the scope of a cyber-physical optimisation framework.

The Green Sustainability Layer is grounded in a structured technology evaluation of Industry 4.0 tools and their measurable environmental contributions. It incorporates four structured sustainability metric clusters: operational resource efficiency (energy consumption per task, equipment efficiency, standby losses, and water consumption); material efficiency and waste reduction (material utilisation rates, rework-related waste, and prefabrication efficiency); carbon and emissions performance (operational and embodied CO₂, equipment emissions); and environmental compliance and circularity (waste-to-value ratios, recycling potential, and lifecycle recovery). Social sustainability dimensions, macroeconomic indicators, and post-occupancy behavioural factors are intentionally excluded, as they are not directly measurable through the selected Industry 4.0 technologies or controllable within MEP construction workflows.

The Industry 4.0 Digital Layer consists of nine evaluated technologies categorised into three functional groups: Core Cyber-Physical Integration Technologies (BIM, IIoT, AI, Digital Twins, and Cloud/Big Data); Process Execution and Augmentation Technologies (Autonomous Robots/Cobots, AR/VR, and 3D Printing); and Data Integrity and Transaction Technologies (Blockchain). The analysis confirms that no single technology independently delivers Lean–Green optimisation; rather, value is generated through coordinated interoperability, where BIM provides data structure, IIoT supplies real-time inputs, AI delivers decision intelligence, Digital Twins enable simulation and feedback, and Execution Technologies translate digital optimisation into physical outcomes.

4.2 Cyber-Physical Lean–Green Loop (CPLGL)

The Cyber-Physical Lean–Green Loop (CPLGL) serves as the central integration mechanism of the framework. It operationalises the interaction between the three layers through a closed-loop control logic consisting of five stages: (1) live site data capture via IoT sensors; (2) BIM/Digital Twin platforms visualise Lean–Green performance; (3) AI analytics interpret deviations and suggest optimisation actions; (4) actions are re-integrated into the workflow; and (5) real-time learning and self-correction close the loop.

The CPLGL transforms the framework from a static structural model into a dynamic, self-optimising system. Unlike traditional project management approaches, which respond to deviations after they occur, the CPLGL enables predictive intervention by continuously comparing physical construction performance against digital performance models. This closed-loop architecture is directly analogous to the cyber-physical production systems demonstrated in Siemens' Amberg factory and Bosch's Lean 4.0 implementation, both of which employ continuous sensing–analysis–action cycles as the basis for adaptive process optimization (Table 1).

Table 1. Technology–Lean–Green contribution matrix within the I4LGF–MEP framework

Technology	Lean Contribution	Green Contribution	Key Framework Role
BIM	Flow optimisation; constraint removal; defect prevention	Reduced material waste; lower embodied carbon	Foundational data environment; enables E-VSM 4.0 visualisation
IIoT	Real-time waste identification; takt monitoring	Dynamic energy and CO ₂ monitoring	Transforms static indicators into sensor-driven feedback loops
Digital Twin	Predictive optimisation; simulation	Lifecycle energy and performance modelling	Enables closed-loop learning (CPLGL)
AI	Root-cause analysis; dynamic scheduling	Resource allocation and emissions reduction	Autonomous Lean–Green optimisation

AR/VR	First-time-right execution; error reduction	Reduced rework; lower material waste	Intuitive decision-making in Lean–Green workflows
Robotics/Cobots	Variability reduction; cycle-time stability	Improved precision; reduced rework waste	Physical execution layer of cyber-physical system
Cloud/Big Data	Information flow; workflow coordination	Sustainability benchmarking and analytics	Scalable data storage, processing, and collaboration
Blockchain	Transparency, traceability, process reliability	Ensures sustainability data integrity	Trusted data governance across Lean–Green systems
3D Printing	JIT production; reduced process waste	Minimise material usage and construction waste	Digital-design-to-automated-fabrication integration

4.3 Environmental Value Stream Mapping 4.0 (E-VSM 4.0)

E-VSM 4.0 extends traditional Lean Value Stream Mapping by embedding real-time environmental indicators—energy usage, carbon emissions, material consumption, and operational waste—directly within operational workflows. The key innovation is the transformation of sustainability assessment from a static, post-project audit into a dynamic, sensor-fed monitoring system visualised within BIM-integrated dashboards.

Core performance indicators tracked by E-VSM 4.0 include: energy consumption per task (kWh/task); carbon intensity per process activity (kgCO₂/task); material utilisation rate (%); rework frequency (events/period); waste generation per activity (kg); and water consumption per process. These indicators are continuously updated through IIoT sensor streams, Digital Twin simulations, and AI-based analytics, enabling sustainability performance to be managed at activity level rather than project level.

4.4 Industry 4.0 Readiness and Maturity Model for MEP Activities

To ensure that digital interventions are calibrated to achievable improvement levels, the framework incorporates a five-level Industry 4.0 readiness scale adapted from established maturity models (IMPULS 2026; Onur Agca 2026). The levels—Level 0 (Traditional), Level 1 (Foundational Digital Awareness), Level 2 (Tactical Integration), Level 3 (Predictive Collaboration), and Level 4 (Closed-Loop Optimisation)—progress from fully manual, reactive execution to autonomous, self-correcting cyber-physical control (Table 2).

Table 2. Industry 4.0 readiness levels applied to MEP activities

Readiness Level	Description	Lean Improvement	Green Improvement
Level 0 – Traditional	Fully manual; paper-based; reactive	None; waste-heavy	High emissions persist
Level 1 – Foundational	Stand-alone sensors; limited integration	Waste visibility only	Partial reduction (simple energy reporting)
Level 2 – Tactical Integration	BIM + IoT linking planning and dashboards	Waste reduction via alerts	Lower energy from improved coordination
Level 3 – Predictive Collaboration	Cross-system integration; AI suggestions	Reduced waiting and transport errors	Measured energy/emissions reductions
Level 4 – Closed-Loop Optimisation	Digital twins; autonomous feedback loops	High variability and rework reduction	High reductions in embodied energy and waste

5. Data Collection

The empirical foundation of the I4LGF–MEP framework is a pilot case study conducted at a power plant process piping installation project at an auxiliary boiler facility in Qatar. The project involved the installation of six-inch stainless steel process piping connecting a new reactor vessel to an existing feed tank, executed within an active industrial facility under strict safety protocols and multi-trade coordination constraints.

Two distinct installation cycles were observed over 33 working days. Cycle 1 involved the installation of prefabricated pipe spools with flanged (mechanically coupled) connections, while Cycle 2 involved field-fabricated spools requiring fusion welding, including the removal and replacement of an existing misaligned pipe section. Data was collected using close-range observation and video recording with two camera angles, enabling detailed post-event analysis of every distinct worker action.

The total observed workforce involvement was approximately 1,450 man-hours, with an average daily crew size of 5.5 workers. All activities were logged, timed, and classified into Value-Adding (VA), Non-Value-Adding (NVA), and Non-Value-Adding but Required (NVAR) categories according to Lean construction principles. Weighted average performance metrics were calculated across all workers and both installation cycles (Table 3, Table 4).

Table 3. Summary of pilot case study value stream performance

Metric	Value
Total Projected Lead Time	33 Working Days
Total Observed Man-Hours	1,450 hrs
Value-Adding (VA) Man-Hours	130 hrs (9.0%)
Non-Value-Adding (NVA) Man-Hours	990 hrs (68.3%)
Non-Value-Adding but Required (NVAR) Man-Hours	330 hrs (22.7%)

Table 4. Waste category breakdown (weighted average across all workers)

Waste Category	Classification	Weighted Average (% of Total)
Waiting	NVA	27.1%
Extra Processing / Rework	NVA	14.3%
Transportation	NVA	11.2%
Motion / Ineffective Work	NVA	16.4%
NVA Total		68.2% (rounded)
Material / Tool Positioning	NVAR	12.5%
Inspection / Safety Setup	NVAR	4.8%
Rigging / Alignment Support	NVAR	5.3%
Value-Adding (Welding, Assembly, Installation)	VA	9.2%

The case study reveals three distinct patterns in the cumulative work distribution lifecycle. NVA time dominates from day one, arising primarily from logistics-related waste before the first pipe spool is lifted. Value-adding hours accumulate in discrete, intermittent steps reflecting sequential bottlenecks in welded and mechanical assembly. A major rework inflection occurs at days 13–15, corresponding to the correction of a pre-existing pipe misalignment, which alone contributed approximately 94 NVA man-hours, equivalent to nearly 10% of total project waste.

6. Results and Discussion

6.1 Lean–Green Coupling Validated by Pilot Data

A critical finding of the case study is that every major Lean waste category has a direct and quantifiable environmental counterpart, confirming the Lean–Green coupling that is central to the I4LGF–MEP framework. The 27% waiting waste corresponds to extended equipment idling and unnecessary energy consumption. The 16% motion and transportation waste generates repeated fuel-intensive material handling, directly inflating Scope-1 carbon emissions. The 14% extra processing and rework waste consumes significant welding energy, abrasive materials, grinding electricity, and shielding gas, while simultaneously increasing embodied carbon through material loss. The 12.5%

material positioning waste reflects push-based logistics that cause repeated unnecessary handling and associated energy consumption.

This causal correspondence between Lean inefficiency and Green underperformance is not incidental; it reflects a structural relationship in which process instability drives environmental burden. When MEP installation operates as a craft-based, batch-driven system, as demonstrated by the 9% VA ratio in the pilot project, sustainability performance is inherently constrained regardless of the sustainability specifications applied at the design stage. This finding validates the framework's fundamental premise: that environmental performance improvement in MEP construction must be achieved through operational process optimisation rather than through design-stage overlays.

6.2 Industrial Benchmarking Validation

The industrial benchmarking analysis confirms that the core cyber-physical integration logic underpinning the CPLGL is not merely conceptual. Siemens' Amberg facility demonstrates that continuous IoT sensing, Digital Twin optimisation, and AI-driven feedback loops can achieve near-zero defect rates through real-time process adaptation (Siemens 2025). Bosch's Lean 4.0 implementation validates the principle that Industry 4.0 technologies deliver maximum value when they augment Lean systems rather than substitute them (Bosch 2023; Kolberg and Zühlke 2015). Toyota's digitally enabled TPS demonstrates that process transparency, jidoka-based quality control, and kaizen cycles can be effectively operationalised through real-time digital monitoring, directly analogous to the CPLGL's sensing–analysis–feedback structure (Liker 2020; Toyota 2025). Volkswagen Autoeuropa's digital transformation confirms that modular system integration and standardised digital workflows can support scalable Lean process control across interconnected production environments (Volkswagen 2023).

A key distinction differentiates the I4LGF–MEP framework from all four manufacturing benchmarks: the explicit structural integration of sustainability as a co-equal performance layer. While manufacturing implementations implicitly achieve sustainability benefits through efficiency improvement, they do not formalise sustainability metrics as independent measurement objectives within their operational architectures. The I4LGF–MEP framework advances this by embedding the Green Layer alongside the Lean and Digital layers, supported by E-VSM 4.0 and the CPLGL, ensuring that environmental performance is managed as an active operational mechanism rather than an emergent efficiency by-product.

6.3 Activity-Level Framework Application

The activity-level Lean–Green–Industry 4.0 mapping demonstrates how the framework operates at the granular process level. Nineteen distinct MEP installation activities were analysed, each mapped against measured waste types, Lean mechanisms, Green impacts, and specific digital enablers. Selected illustrative activities are discussed below. Material delivery to the laydown yard (Activity 1) was characterised by approximately 20% inventory-related NVA/NVAR time arising from push-based delivery logistics, batch shipments, and absence of real-time inventory visibility. The I4LGF–MEP response integrates RFID-based material tracking linked to BIM–ERP systems, AI-driven Just-In-Time logistics planning, and digital laydown yard allocation. Expected outcomes include a conversion from push to pull logistics, significant reduction in inventory dwell time, and measurable decreases in handling energy, idling equipment emissions, and Scope-3 transport carbon.

Field cutting to length (Activity 3) exhibited approximately 10–15% extra processing waste arising from manual interpretation of drawings, dimensional uncertainty, and lack of integration between BIM geometry and field fabrication. The framework response deploys BIM-to-fabrication digital geometry control, AI-assisted cut optimisation, and laser-based as-built verification. The causal logic is: BIM defines geometry → AI predicts optimal cut → digital instructions guide execution → laser verifies compliance → quality data updates Digital Twin → continuous improvement loop is established. Expected Lean outcomes include near elimination of over-cutting and rework; expected Green outcomes include scrap reduction from approximately 10–15% to 4–6% per installed spool. Production welding (Activity 14) represents the primary VA activity yet is constrained by rework and overprocessing waste consuming approximately 22% of observed time around this stage. The framework integrates IoT-enabled welding machine monitoring, AI-based weld quality prediction using Weld Data Monitoring Systems (WDMS), BIM-aligned joint positioning, and predictive defect analytics. The expected result is a systematic reduction in weld failure rates, corresponding decreases in rework energy, electrode waste, shielding gas emissions, and embodied carbon loss per joint (Table 5).

Table 5. Lean–Green–Digital causal alignment for selected MEP activities

Dominant Waste	Lean Root Cause	Green Impact	I4.0 Resolution
Waiting (27%)	Poor sequencing; equipment bottlenecks	Idle equipment energy; extended emissions	AI scheduling; CPLGL real-time coordination
Motion (16%)	Manual alignment; poor spatial planning	Repeated fuel use; handling emissions	AR + Digital Twin alignment verification
Extra Processing (14%)	Quality defects; rework cycles	Re-welding carbon; grinding energy	CPS sensor feedback; weld quality AI
Transportation (11%)	Push logistics; remote laydown	Fuel use; Scope-1 emissions	RFID + AI pull logistics systems
Inventory (12%)	Batch delivery; no readiness signalling	Storage energy; material degradation	BIM–ERP JIT release + Digital Twin

6.4 Modular MEP Structure and Scalability

The modular architecture of the I4LGF–MEP framework allows each MEP subsystem—HVAC, plumbing, electrical, fire protection, and infrastructure—to be treated as an independently optimisable yet interconnected module. Within each module, the tri-layer architecture is applied in a targeted manner: the Lean layer identifies and addresses the specific waste patterns dominant in that subsystem; the Green layer defines the environmental metrics most relevant to the module's operational profile; and the Digital layer deploys the most suitable Industry 4.0 technologies based on the subsystem's production logic.

Module-specific KPIs and performance benchmarks can be established for each subsystem and aggregated at the project level. This approach reduces implementation risk by enabling phased adoption—beginning with the highest-impact module and expanding incrementally—while maintaining system-wide coherence through the CPLGL and shared data environments.

6.5 Theoretical and Practical Implications

The I4LGF–MEP framework makes several contributions beyond the specific domain of MEP construction. Theoretically, it extends the emerging concept of Lean Construction 4.0 into a broader Lean–Green 4.0 paradigm by introducing sustainability as a co-equal structural dimension rather than a secondary efficiency outcome. It advances cyber-physical systems theory in construction by providing a specific operational architecture—the CPLGL—that integrates physical construction activities with digital intelligence through continuous feedback. It also introduces E-VSM 4.0 as a new analytical tool that extends Lean toolset methodology to incorporate real-time sustainability analytics.

Practically, the framework provides construction organisations with a structured, replicable roadmap for digitally transforming and decarbonising MEP operations. The maturity-calibrated readiness model enables organisations to identify their current Industry 4.0 capability and plan realistic improvement pathways. The activity-level Lean–Green–Digital mapping tables provide direct decision support for technology selection, process intervention prioritisation, and KPI definition. The E-VSM 4.0 instrument enables continuous environmental monitoring throughout project execution, shifting environmental management from periodic compliance reporting to live performance optimisation.

7. Conclusion

This paper has presented the development and characterisation of the Industry 4.0–enabled Lean–Green Framework for MEP Construction Systems (I4LGF–MEP). The framework addresses the persistent three-way fragmentation between Lean process management, sustainability assessment, and Industry 4.0 technology adoption that characterises current MEP construction practice.

The framework's tri-layer architecture integrates Lean process optimisation, Green sustainability performance, and Industry 4.0 digital intelligence within a unified operational structure, governed by the Cyber-Physical Lean–Green Loop (CPLGL). The CPLGL enables continuous sensing, analysis, and adaptive optimisation, transforming the framework from a static model into a self-learning cyber-physical system. Environmental Value Stream Mapping 4.0

(E-VSM 4.0) operationalises sustainability at activity level by embedding real-time environmental indicators within operational workflows. The maturity-based readiness model ensures that digital interventions are calibrated to realistic improvement levels, avoiding technology-driven abstraction.

The pilot case study provides empirical grounding: the 9% VA ratio observed in a power plant piping installation confirms that MEP construction in its traditional form operates as a craft-based batch system rather than a flow-oriented production system, and that this structural inefficiency simultaneously constrains both process performance and sustainability outcomes. The industrial benchmarking analysis confirms that the cyber-physical integration logic underpinning the I4LGF–MEP framework is practically demonstrated in advanced manufacturing environments, while also confirming that the framework's explicit Green layer and construction-domain adaptation represent novel advancements beyond existing industrial implementations.

The key original contribution of the study is the establishment of a causal, process-level logic in which Lean waste reduction, sustainability improvement, and Industry 4.0 digital integration are treated not as competing priorities but as structurally interdependent outcomes of the same operational transformation. Digitalisation delivers value in MEP construction only when technologies are clearly aligned with Lean mechanisms and sustainability metrics within a unified cyber-physical architecture.

Future research should address the empirical validation of the framework through the Delphi expert consensus method, and the development of the Green–Lean Conformance Instrument (GLCI) for real-time performance measurement and benchmarking across MEP project environments.

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