AN EDGE-ORIENTED INDUSTRY 4.0 SOLUTIONS NETWORK FOR CABLE HARNESS TESTING EQUIPMENT MANUFACTURING

Filip Mitrevski[1], Pece Mitrevski[2] and Silvana Angelevska[1]

[1]Department of Industrial Engineering and Management, Faculty of Technical Sciences, University "St. Kliment Ohridski", Bitola, North Macedonia
[2]Faculty of Information and Communication Technologies, University "St. Kliment Ohridski", Bitola, North Macedonia

ABSTRACT

The cable industry faces growing pressure to remain highly flexible and supply the wide range of cables the automotive sector requires. This pressure also affects companies that provide cable harness testing equipment to ensure that inspection and testing are performed as reliably as possible. This study aims to support the planning of an Industry 4.0 (I4.0) solutions network that is compatible with diverse companies across various industries, particularly in highly customized manufacturing environments. It examines a holistic reference model for the production process of a cable harness testing equipment company to identify optimization opportunities and gaps that could be addressed through I4.0 technologies. The paper proposes a qualified seven-stage solutions network interconnected through an IoT-based system. The identification layer specifies a secure 13.56 MHz HF-RFID/NFC credential and treats Data Matrix as a conditional worksheet choice based on compactness and standards adoption, or as a direct-part-marking option when lifecycle traceability is required. The architecture also incorporates an edge database and edge computer vision. Practitioners could use this framework as a foundational template for highly customized, data-intensive industrial applications, subject to empirical validation and adaptation to the specific production context.

KEYWORDS

Industrial Internet of Things (IIoT), Edge Computing, Shopfloor Orchestration, Cable Harness Testing, Reference Architectural Model

1. INTRODUCTION

Cable harnesses are critical components governing modern vehicle performance, reliability, and safety. Faulty or misaligned harness assemblies can lead to catastrophic system failures and severe accidents. That is why the industry demands rigorous quality standards alongside robust manufacturing and validation protocols. Developers face a number of operational challenges, such as managing low-volume and high-variant product lines, maintaining short cycle times, diagnosing latent electrical faults that pass standard static continuity checks but fail under dynamic field conditions, etc. To address these vulnerabilities, a growing body of research and architectural frameworks approach cable harness testing as a combined electromechanical [1]and data-centric problem[2].

Optimizing the testing procedure itself is paramount. But a critical engineering bottleneck resides in the physical design and manufacturing of the testing equipment. Unlike the high-volume lines of the harnesses they evaluate, the production of Automated Test Equipment (ATE) is a low-

volume, hyper-customized manufacturing endeavor. Equipment builders must synthesize high-density electromechanical interfaces with complex matrix-switching circuitry and real-time data acquisition hardware[3]. Consequently, manufacturing these machines requires strict adherence to tight geometric tolerances, advanced noise-isolation techniques, and modular architectural frameworks to keep the equipment scalable, maintainable, and resilient to shop floor wear.

These production complexities need to be systematically addressed.This study supports the planning of an Industry 4.0 (I4.0) solutions network designed specifically for highly customized manufacturing environments across diverse industries. By evaluating an existing holistic reference model for the production processes of a cable harness testing equipment manufacturer, this study identifies opportunities for operational optimization and systemic process gaps. Ultimately, this work proposes several targeted I4.0 technological interventions.

Because the wire harness testing industry combines electrical validation, extensive data traceability, and customized low-volume hardware manufacturing, Section 2 draws on both industry-specific and general manufacturing models to establish a comprehensive architectural baseline. Section 3 examines the holistic reference model, while Section 4 presents a qualified seven-stage solutions network that specifies an HF-RFID/NFC credential and reader stack, evaluates Data Matrix conditionally for worksheet compactness or direct part marking, and introduces an edge database and edge computer vision. Finally, Sections 5 and 6 discuss the expected advantages, limitations, and validation requirements of implementing such a network in a real-world context and present the main conclusions.

2. RELATED WORK

In order to extend the Reference Architectural Model for Industry 4.0 (RAMI 4.0)[4], European automation consortiums developed the Asset Administration Shell (AAS) [5]for the Wiring Harness System. It explicitly translates the physical components of a wire harness into a standardized, interoperable digital twin metadata structure. The AAS model provides the exact data dictionary and Application Programming Interface (API)shell structure for how the testing machine reads, interprets, and shares data about the harness under test.

The Model-Based Wiring Harness Engineering / Comprehensive Digital Twin (Siemens Capital Flow)[6]is a globally recognized commercial reference architecture for end-to-end digital threads in wire harness design, costing, and validation. This model focuses heavily on merging the logical electrical design (schematics) directly with the physical manufacturing model (form boards). Using this as a reference guarantees that the testing equipment reference model can dynamically ingest a customer's CAD data to instantly map out pin-to-pin validation requirements without manual software intervention.

ISA-95 (Enterprise-Control System Integration) [7]is the standard for mapping manufacturing control systems. It splits a manufacturing enterprise into five strict functional levels:

- Levels 0and1: The physical process and sensors (e.g., test blocks, pins, continuity probes);
- Level 2: Automated execution control (e.g., PLCs, tester microcontrollers running continuity loops);
- Level 3: Manufacturing Execution Systems (MES) (e.g., quality control gates, automated PASS/FAIL recording, defect rework logging);
- Level 4: Enterprise Resource Planning (ERP) (e.g., business planning and high-level inventory logistics).

It is fully compatible with I4.0 and defines exactly where the “testing hardware” software ends and where the factory’s broader “management” software begins.
The Purdue Enterprise Reference Architecture (PERA) [8]is a foundational master model for Enterprise Architecture. It models the complete lifecycle of an industrial plant or product line across three core tracks: the Information/Data architecture, the Physical Equipment/Human interface track, and the Organizational policy track.

While PERA gives the broader philosophical blueprint to document how the engineering teams, corporate policies, and physical manufacturing spaces interact globally, the Industry 4.0 Conceptual Model Proposal for Cable Harness Testing Equipment Industry by Rosa et al. [9]acts as a highly focused “solutions network” for the shop floor where testing equipment is machined. It specifically targets the highly customized machining and assembly process of building wire harness test tables. This conceptual model consists of seven interconnected stages linked through an Internet of Things (IoT)-based wireless network. It is intended to improve several stages of the machining process used to manufacture cable harness testing table components. By combining software and supporting technologies, the model aims to reduce process failures and shorten production time, which is why it was selected as the holistic reference model described in the following section.

3. THE REFERENCE HOLISTIC PROPOSAL MODEL

3.1. Description of the Network of I4.0 Solutions

To create a production environment that can meet each customer’s specific requirements, reduce production time across several stages, and maintain the flow of the manufacturing process, the case company of [9]planned a network of I4.0-based solutions. The network followed a mass-customization-oriented approach so that it could be adapted to the company’s specific configuration.

The I4.0SN (Industry 4.0 Solutions Network), schematized in Figure 1, consists of seven stages connected through the organization’s network, following an approach based on the IoT concept. The system aims to improve several activities in the machining process through software and enabling technologies, leading to a manufacturing process that is less prone to failures and has a shorter, more predictable production time.

The network's general workflow begins with a factory worker identifying themselves at the workstation using a Radio-Frequency Identification (RFID) card. Once this step is complete, the Quick Response (QR) code associated with that project, previously printed on the project worksheet, would be read, and the information encoded in it would trigger two procedures: selecting all information related to the project and identifying the machining-process stage the project is currently in.

By cross-referencing these two pieces of information, the system would automatically provide the drawings needed at that specific workstation at that specific moment, avoiding information overload. The drawings would automatically display on a computer screen at that workstation, and the machining process for each piece would proceed according to the information they contain. Finally, the pieces would undergo an automated quality-control technique based on a Computer Vision System (CVS) that would compare each piece’s characteristics with its corresponding drawings, identify any possible defects, and report them accordingly. This task flow occurs at each workstation in the machining process.

4. TECHNOLOGICAL OPTIMIZATIONS FOR THE BASELINE REFERENCE MODEL

Building on the reference model, this paper proposes an improved seven-stage network interconnected through an IoT-based system. The proposed changes refine the operator credential from an unspecified "RFID card" to a defined 13.56 MHz HF-RFID/NFC credential, replace worksheet QR codes with Data Matrix where compactness or standards-based encoding provides a documented benefit, move the centralized company database to an edge database, and move conventional computer vision to edge execution(Table 1).

Table 1. Baseline-versus-improved design-selection matrix

Design change	**Baseline and unresolved evidence**	**Proposed specification**	**Defensible selection criteria**
Unspecified RFID credential → defined HF-RFID/NFC credential	[9] identifies only an "RFID card"; it does not report LF, HF, or UHF frequency, air-interface standard, chip class, reader model, range, or authentication method. An access/proximity card may already be 13.56 MHz HF RFID under ISO/IEC 14443, so NFC is not inherently an alternative to the baseline.	NFC is a subset/profile of HF RFID operating at 13.56 MHz and building on ISO/IEC 14443 and ISO/IEC 18092. For operator authorization, an ISO/IEC 14443-4 credential with cryptographic mutual authentication, e.g., an AES-capable MIFARE DESFire EV3 application [10]with diversified per-card keys, protected key storage in the reader or secure access module, and backend authorization could be specified. Smartphone interoperability may then be an additional NFC requirement rather than the security mechanism itself.	Read range Security Compliance Cost
Worksheet QR Code → worksheet Data Matrix, or direct part marking	The current model prints a QR Code on a paper project worksheet. QR Code (ISO/IEC 18004:2024) and Data Matrix ECC 200 (ISO/IEC 16022:2024) both use Reed-Solomon error correction; neither symbology provides confidentiality, authentication, or "information security" by itself [11], [12]. On paper, durability depends mainly on media, print quality, handling, contrast, quiet zone, and symbol verification.	For the existing worksheet workflow, Data Matrix is justified if tests show that its compact footprint, one-module quiet zone, encoding efficiency, scanner compatibility, or adoption of GS1 Application Identifiers is preferable for the actual payload. A stronger traceability redesign would mark each physical part directly with Data Matrix and retain the worksheet code only as the job/document identifier.	Capacity/error correction Direct part marking Security Cost

Centralized database → edge database	A centralized server simplifies governance and master-data control but makes workstation access dependent on LAN/WAN availability and adds network round-trip delay to each read or write.	An edge database keeps the execution subset and write queue near the workstation, continues local reads/writes during an upstream outage, and synchronizes later. Large-scale measurements found that 58% of users reached an edge server in under 10 ms versus 29% reaching a cloud location in under 10 ms[13].	Offline operation Latency budget Cost Compliance
Centralized computer vision → edge computer vision	Cloud or central-server inference offers elastic compute and centralized model management, but every inspection includes image upload, network variability, remote inference, and response transport; loss of connectivity can suspend inspection.	Edge inference keeps image processing beside the camera and can continue offline. Edge locations more frequently achieve sub-10-ms transport latency [13]. A representative Jetson Orin Nano Super developer kit provides up to 67 TOPS (Trillions of Operations Per Second) [14].	Latency budget Offline operation Cost Compliance

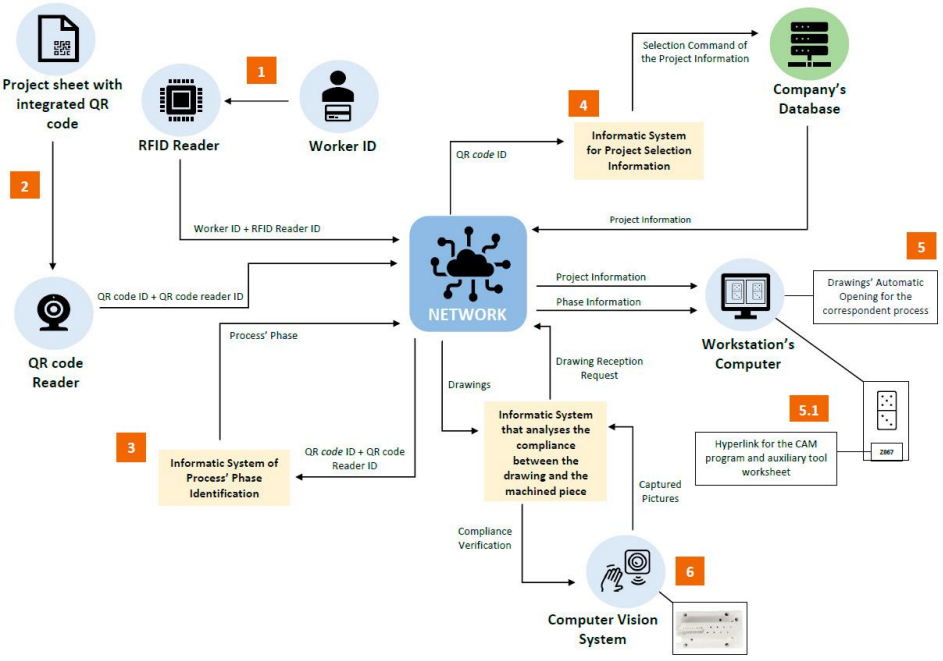


Figure1. I4.0SN in the reference proposal model. Reproduced from [9] under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives 4.0 International License (CC BY-NC-ND 4.0).

4.1. Specification of an HF-RFID/NFC Credential

Near Field Communication (NFC) [15] is not a technology outside RFID. It operates at 13.56 MHz and is a subset/profile of HF RFID, combining contactless interfaces based on ISO/IEC 14443 and ISO/IEC 18092 with NFC Forum interoperability specifications. The reference model in [9] describes an "RFID card" but does not identify its frequency band, air interface, chip, reader, range, or authentication method.

The defensible design change is therefore from an unspecified credential to a defined secure HF-RFID/NFC credential and reader stack. For example, an Advanced Encryption Standard (AES)-capable MIFARE DESFire EV3 application [10]could use diversified per-card keys, mutual challenge-response authentication, protected key storage in the reader or a secure access module, transaction freshness, and backend role authorization. A UID-only card must not be treated as an authenticated identity because its static identifier can be copied or emulated. Short range can reduce unintended reads, but it does not prevent eavesdropping, cloning of weak credentials, or relay attacks. NIST documents NFC relay as a man-in-the-middle threat [16]. NFC should consequently be selected for deliberate tap interaction and smartphone/card interoperability, while security claims must be tied to the named credential, protocol, key-management, and user-presence controls.

4.2. Conditional Use of Data Matrix for Worksheets or Direct Part Marking

A Data Matrix code is a two-dimensional barcode composed of black-and-white cells arranged in a square or rectangular grid[17]. It can encode textual or numerical information compactly, with capacity depending on symbol size and the number of cells. Data Matrix ECC 200 and QR Code are both standardized two-dimensional symbologies (under ISO/IEC 16022:2024 and ISO/IEC 18004:2024, respectively) and both use Reed-Solomon error correction [11], [12]. Neither symbology provides confidentiality, authentication, or improved information security.
For the paper worksheet used in the reference model, its potential advantage over QR Code is limited to criteria such as symbol footprint, one-module quiet-zone requirement, encoding efficiency for the actual payload, scanner compatibility, and adoption within a chosen data standard such as GS1.If an identifier is marked on the physical part, the improved model should add a verified direct Data Matrix mark to each suitable part (following applicable requirements such as SAE AS9132 or MIL-STD-130) and retain the worksheet symbol as a separate project/document identifier[17].

4.3. Edge Database

Data generation is becoming increasingly decentralized. On the other hand, conventional cloud-computing infrastructures remain largely centralized. Transferring all decentralized data to a central cloud environment can therefore be inefficient, costly, and technically impractical. In some industrial scenarios, such an approach may also introduce unnecessary latency, bandwidth consumption, and operational dependency on network availability.

To support digital transformation and create value from decentralized data, cloud computing can be complemented by edge computing [18], [19], [20]. Edge computing places computational resources close to the point where data is generated and thereby decentralizes selected data-storage and processing functions. Subject to the workload, hardware, network, and software design, this approach may support faster local decision-making and reduce the need to transmit raw data continuously to remote cloud infrastructure.

An Edge Database can form a core element of edge data management [21]. Depending on the selected product and configuration, it may provide persistent local storage, support decentralized data flows, and synchronize data among devices or between edge and cloud environments. These capabilities could reduce application-specific development effort, but synchronization logic, conflict resolution, security, backup, and recovery would still require explicit design and validation.

Most IoT and industrial applications require some form of local storage, synchronization, or historical data access. An Edge Database is particularly useful when an application must satisfy one or more of the following conditions:

- operation must continue offline and independently of an internet connection;
- a fast response time must be guaranteed;
- large volumes of, possibly high-frequency, data must be handled;
- many devices must be served at the same time;
- historical data is required.

Looking ahead, on-device vector databases and small language models may further extend the role of edge databases in industrial systems. These technologies could support local artificial-intelligence applications by providing memory, context, and access to relevant data on the device. Local processing may reduce dependence on continuous cloud connectivity and bandwidth consumption. Any privacy, scalability, sustainability, or response-time benefit would depend on the data retained locally, the model and hardware, the security controls, and the measured workload.

4.4. Edge Computer Vision

Several technical conditions have to be satisfied in order to migrate computer vision to the edge. First, an appropriate edge device must be available. For computer-vision workloads, devices equipped with a graphics processing unit (GPU) or visual processing unit (VPU) are preferable because they can process visual data more efficiently. Although edge devices are often associated with IoT hardware, any device capable of capturing, processing, and interpreting visual information can potentially function as an edge computer-vision node.

Assuming suitable hardware is available, the next requirement is deployment of a validated computer-vision application. One possible approach is to deploy the application from a managed platform to the edge device and execute inference locally. After deployment, the device could continue processing visual data during loss of cloud connectivity if the model, dependencies, storage, and control logic are available locally. Any latency or availability improvement would need to be measured against the selected centralized alternative under representative network and workload conditions.

Edge computer vision may be relevant in industrial environments that require time-sensitive monitoring or automated inspection. Software deployed near cameras, sensors, and production equipment could analyze selected production steps locally and report process anomalies with limited network dependency. Edge-based visual monitoring may also support measurement of process cycle times and identification of potential bottlenecks. Cameras combined with validated edge-deployed software could inspect products and flag suspected defects before they proceed to later stages. Detection accuracy, false-positive and false-negative rates, cycle-time impact, and operator response would require empirical evaluation.

In smart-factory architectures, artificial intelligence (AI) and machine learning (ML) can be used to analyze visual data, support system management, and improve production processes over time. An example architecture based on Microsoft Azure [22] illustrates an end-to-end approach to IoT computer vision in manufacturing, where cameras send images to an Azure IoT Edge device running a machine-learning model. The model performs inference locally and transfers selected outputs to the cloud for further processing, while human interventions can be incorporated into

the learning cycle. This cycle typically involves training, testing, tuning, and validating the machine-learning algorithms.

For manufacturing companies, edge computer vision may support faster inspection, lower bandwidth use, reduced transfer of sensitive visual data, and lower latency when compared with a centralized design. These outcomes depend on the model, image resolution, edge hardware, network path, retention policy, and integration architecture. Implementation would require investment in cameras, edge hardware, model development, validation, monitoring, maintenance, and integration with existing production systems. Whether those costs are justified must be established through a site-specific business case and pilot measurements of quality, rework, throughput, bandwidth, and availability. Edge computer vision is therefore a candidate optimization for the proposed network rather than a demonstrated improvement.

4.5. Schematic Representation of the Improved Proposal Model

4.5.1. Proposal Concept

The proposed solutions network, schematized in Figure 2, consists of seven stages using integrated technologies and programs connected through IoT tools. The network is intended to automate selected part-processing activities and is hypothesized to reduce processing time and failure frequency. These outcomes have not been demonstrated and should be tested against the baseline under representative production conditions:

- The first step consists of identifying the operator with a defined secure 13.56 MHz HF-RFID/NFC reader and ISO/IEC 14443-4 credential using AES-based mutual authentication(1);
- When the machining process begins, the workstation reads the project identifier from the worksheet. Data Matrix is used if payload-and-print testing demonstrates a compactness, quiet-zone, scanner-compatibility, or standards-adoption benefit over QR Code.If lifecycle part traceability is required, a separate verified Data Matrix mark is applied directly to each suitable part (2);
- The project identifier and the corresponding reader deliver information to the network and trigger two procedures:
    - identification of the machining stage in which the current process is located (3);
    - selection of all project-related information from the edge database (4);
- Based on the intersection of these two pieces of information, the system automatically provides the workstation computer/tablet with drawings of the parts to be machined, without any need for operator intervention (5 and 5.1);
- After the parts are machined, they undergo quality inspection using an edge CVS (6);
    - This system is integrated with software, following the example of an IoT computer-vision architecture in manufacturing based on Microsoft Azure, which indicates whether the part is within conformity limits. If nonconformity is identified, the system provides information about its location on the CVSscreen;
- The workstation components communicate through a segmented industrial wireless and Ethernet architecture rather than a single logical hub. The assumed wireless access layer is industrial Wi-Fi 6 (IEEE 802.11ax) with redundant access points, separate Operational Technology Virtual Local Area Networks (OT VLANs), WPA3-Enterprise/802.1X authentication, radio-site qualification, and wired industrial Ethernet for the vision camera, edge gateway, CNC interface, and any control path that requires predictable bandwidth. A private 5G standalone network with a local user-plane function is an

alternative where plant coverage, mobility, interference control, or contractual quality-of-service requirements justify its additional infrastructure and operating cost.

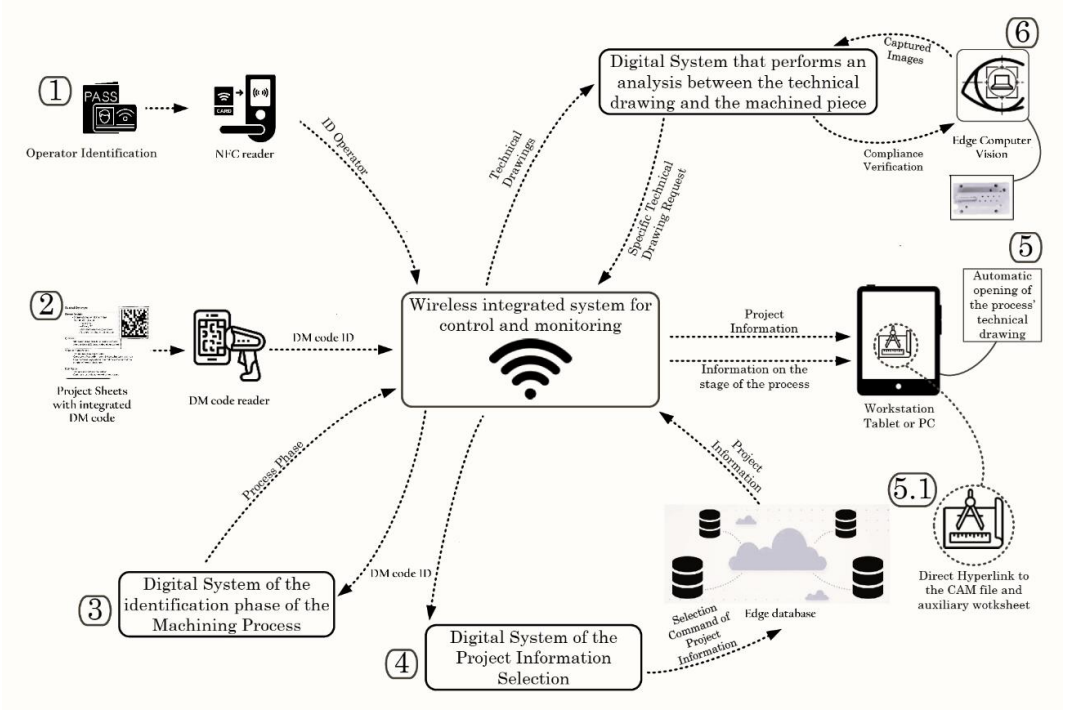


Figure2. Schematic representation of the improved proposal model. Adapted from [9]

The proposed IoT-based network is expected to accelerate the machining process and may reduce events that cause production interruptions, delays, and resource losses. However, there are some challenges in implementing such a system: imposing a sequence of parts to be processed at each workstation may make the system less flexible. In addition, the parameterized nature of the CVS assessment may have some drawbacks, such as identifying nonconformity in a part that, considering its purpose and function, may not be regarded as such in practice, leading to loss of time and resources.

In addition, there are situations to which the system cannot respond. Operational issues, such as shift changes or the simultaneous operation of more than one Computer Numerical Control (CNC) machine, are examples in which automating these activities may create an additional structural and/or financial problem.

4.5.2. Layout of the Physical Components

The diagram in Figure 3 captures the layout of the physical components of the set of technologies that make up the network system at the workstation in the production plant. In this figure, the CNC machine may be replaced by any other machine used in the process.Strong interoperability among sensors and actuators is essential for a flexible and dynamic production line. To communicate with one another, I4.0 devices must be properly integrated into production environments. In fact, effective interoperability is essential for the network of I4.0 solutions to operate steadily, because different heterogeneous devices must be combined with one another to achieve a common goal.

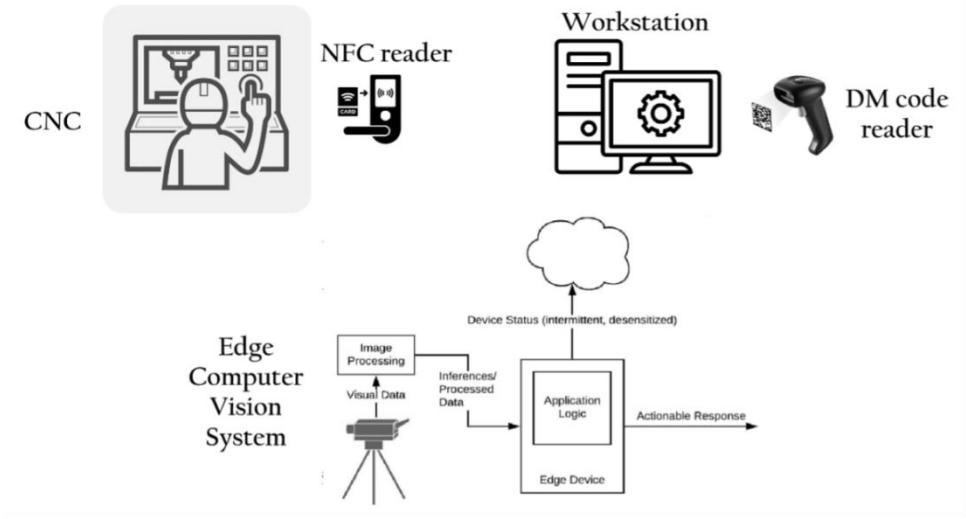


Figure3. Layout of the physical components. Edge computer vision segment adapted from [23]

4.5.3. Edge-to-Enterprise Control Logic

The proposed control logic is intended to link shopfloor execution to enterprise-level governance through a layered architecture. Secure HF-RFID/NFC readers, barcode scanners, CNC controllers, test instruments, and vision stations connect to a workstation-level edge gateway over wired industrial Ethernet where deterministic behavior or high throughput is required, and over industrial Wi-Fi 6 for mobile terminals and non-critical telemetry. The gateway terminates device protocols, validates identities and timestamps, normalizes payloads, buffers events, and routes data to the local edge database and enterprise integration services. Private 5G with a local core is a deployment alternative rather than an additional mandatory layer.

Protocol mapping. At the device layer, CNC machines, PLCs, test instruments, and smart cameras expose data to the gateway through Open Platform Communications Unified Architecture (OPC UA)[24]client/server, vendor-specific industrial Ethernet drivers, or GigE Vision where applicable. The gateway publishes normalized production events through Message Queuing Telemetry Transport (MQTT) 5.0 over Transport Layer Security (TLS) 1.3[25]. The edge database is accessed through a local authenticated API or database driver.Enterprise MES/ERP integration uses versioned HTTPS/REST interfaces, while AAS Repository, Registry, Discovery, and Submodel services use the IDTA-01002 HTTP/REST APIs [26].

Vision traffic and timing. The vision camera should use a dedicated wired link to the edge vision node (raw image streams should not traverse the shared wireless network). Uncompressed payload is calculated as width × height × frame rate × transmitted bits per pixel. As an indicative design point, 1920 × 1080 monochrome images at 30 frames/s and 8 bits/pixel generate approximately 498 Mbit/s before Ethernet overhead, while 5-megapixel monochrome images at 30 frames/s generate approximately 1.2 Gbit/s.The camera interface and switch uplink should therefore retain at least 20% engineering headroom [27]. Only the inspection result, thumbnail, feature vector, and exception images are normally sent through MQTT to the gateway.Full-resolution images are retained locally according to the quality-record policy and uploaded asynchronously. These figures are acceptance targets to be verified with the selected camera, model, hardware, and network.

Synchronization and conflict resolution. Shopfloor observations are append-only, uniquely identified events stored first in a durable local outbox and forwarded asynchronously to the enterprise broker and historian. Connectivity loss therefore delays upstream visibility but does not stop local event capture. Master data, approved work instructions, drawings, models, and access-control policy flow only from their authoritative enterprise systems to the edge.

Availability and fault containment. The centre of Figure 2 represents a logical integration plane, not one physical server or radio. The production cell should have two independently powered industrial access points with overlapping qualified coverage, redundant managed switches, and a pair of edge gateways operating active/standby with replicated configuration and a virtual service address. Each workstation retains the currently released job package and a local event queue, so loss of an access point, gateway, broker, database node, or uplink degrades synchronization and supervision without immediately stopping an already authorized operation. Safety functions and machine motion remain local and independent of this architecture.

Engineering source of truth and revision integrity. The product-lifecycle-management or engineering-document-management system remains the sole authority for released drawings and models. A release service publishes a package containing the document identifier, revision, lifecycle state, applicability/effectivity, file hash, approval signature, and release timestamp through the AAS Repository/Submodel APIs or a controlled enterprise REST endpoint [26]. The edge gateway downloads the package to a read-only cache, verifies its signature and hash, and records successful activation before exposing it to a workstation. At job start, and again before a critical operation, the workstation compares the job's required revision with the locally activated package and, when connectivity exists, with the authoritative release manifest. A newer or revoked revision invalidates the cached package and blocks new work until the approved package is downloaded and verified. During an outage, only a previously verified package within a defined offline-validity window may be used.

Governance & value. The proposed event schema should require time, authenticated identity, asset or job, operation, required revision, executed package hash, and result. Features described above are proposed safeguards whose effectiveness would require security and operational validation. Revision integrity is therefore an acceptance property (demonstrated when the workstation rejects stale, revoked, unsigned, or mismatched content) not an automatic benefit of replication. Other expected benefits include less paper handling and search time, earlier defect detection, more complete genealogy, and faster continuous improvement.None of these outcomes has yet been demonstrated in the target production environment.

5. IMPLEMENTATION REALITIES AND SYSTEMIC TRADE-OFFS

5.1. Operational Catalysts and Strategic Model Advantages

5.1.1. Expected Advantages of a Defined Secure HF-RFID/NFC Credential

Generally speaking, I4.0 is characterized by the integration of cyber-physical systems, IoT-based connectivity, and data-driven decision-making into manufacturing environments. Communication technologies influence how reliably operators, machines, tools, and information systems exchange data. NFC should not be compared with RFID as if the two were separate technology families: NFC operates at 13.56 MHz and is a subset/profile of HF RFID based on ISO/IEC 14443 and ISO/IEC 18092. The relevant design question is whether the unspecified "RFID card" in [9] is LF, HF, or UHF, and whether a more precisely specified secure HF-RFID/NFC credential offers a documented operational benefit [28].

A short-range HF-RFID/NFC interaction can support deliberate presentation of a credential at a specific workstation and may reduce unintended reads. But proximity alone does not authenticate the operator or prevent copying, emulation, eavesdropping, replay, or relay. The proposed access-control profile therefore names an ISO/IEC 14443-4 cryptographic credential using AES-based mutual challenge-response authentication, diversified per-card keys, protected reader-side key storage, transaction freshness, and backend role authorization. UID-only identification is excluded because static identifiers can be cloned, and relay attacks remain a documented threat even when the legitimate card performs cryptographic operations [16].

RFID spans multiple frequency bands, air interfaces, reading distances, and credential classes. LF and HF proximity systems are commonly used for intentional presentation, whereas UHF systems can support longer-range or bulk identification in logistics and material flow. Because [9] does not identify the installed band or credential class, this paper does not claim that NFC is categorically better than the baseline. It proposes a secure HF-RFID/NFC profile for tasks requiring deliberate tap interaction, cryptographic mutual authentication, and optional interoperability with compatible mobile devices.

The expected operational advantage is deliberate, short-range interaction. An operator must bring the credential or device close to the reader, which may reduce accidental reads and ambiguity about which workstation is being addressed. Authorization security depends on the selected card class and implementation. A tap-based HF-RFID/NFC workflow is expected to support simple and intuitive interaction and could be integrated into daily production activities without extensive training. This simplicity reduces implementation friction and supports faster shopfloor acceptance, especially when the same NFC-enabled devices can serve multiple functions such as login, status confirmation, and information retrieval.

Some smartphones and tablets include NFC interfaces and may serve as supplementary interaction points for compatible workflows. This does not remove the need for an industrial reader, secure credential provisioning, protected keys, device management, and application integration. Any infrastructure or cost benefit must therefore be demonstrated for the selected devices and security architecture rather than attributed to NFC availability alone.

In the proposed network, a defined secure HF-RFID/NFC credential is expected to support operator accountability, maintenance logging, and workstation-specific interaction. These benefits depend on successful mutual authentication and backend authorization.They must not be attributed to NFC proximity or to the card UID alone. The proposal should be validated against cloning, replay, relay, lost-card, key-compromise, and reader-tampering scenarios before access-control benefits are claimed.

5.1.2. Conditional Advantages of Data Matrix

Data Matrix can provide a compact standards-based identifier for digitalized production environments, but its suitability depends on where and how it is used. On the paper worksheet in the reference model, the relevant comparison with QR Code is symbol footprint, quiet-zone requirement, payload efficiency, print quality, reader compatibility, and adoption of a chosen data standard. Readability under demanding industrial conditions cannot be inferred from the symbology alone.

Like QR Code, Data Matrix can serve as a machine-readable pointer to project data, batch information, inspection records, maintenance histories, or a digital representation held in connected systems. These functions arise from the identifier schema, database, and application

workflow rather than from the barcode itself. The printed symbol remains copyable and should not contain sensitive information or be treated as proof of authenticity without separate application-level controls.

A potential advantage of Data Matrix is high data density within a compact symbol. That benefit should be demonstrated by encoding the same production identifier in both QR Code and Data Matrix at the available print resolution and verifying each symbol with the intended scanners. Data Matrix ECC 200 provides Reed-Solomon error correction, but QR Code does as well. For a paper worksheet, the defensible potential benefit is a smaller symbol or quiet zone for the required identifier and alignment with a selected data standard. Durability and lifecycle traceability become meaningful advantages if the Data Matrix is directly marked and verified on the physical part under an applicable marking standard [12],[17].

5.1.3. Expected Advantages of Using an Edge Database

An Edge Database could support the proposed model by moving selected data-storage and processing functions closer to the point where data is generated. Rather than relying exclusively on centralized infrastructure, production data could be stored temporarily or persistently on configured edge devices or gateways. This architecture may be valuable where measured requirements include low latency, local autonomy, or continued access to operational data, but the benefit depends on the replication design, workload, network reliability, storage capacity, and recovery procedures.

Processing data near its source is expected to reduce the volume of raw information transmitted to upstream systems when local filtering and aggregation are appropriate. Sensor readings, machine events, operator actions, and inspection results could be filtered, organized, and stored locally before selected data are synchronized with enterprise or cloud platforms. This design may reduce network traffic and response time and may support faster workstation-level decisions, but these effects should be measured against the centralized baseline using the proposed latency, throughput, and availability criteria.

Edge databases are also expected to improve operational resilience because they can be configured to continue functioning during temporary network outages. As a result, production systems may maintain access to the information needed for execution, monitoring, and quality control when connectivity to the central infrastructure is interrupted. This offline capability could be important for production environments that cannot tolerate frequent delays or dependence on continuous internet availability.

In a factory context, an Edge Database could store machine data, production events, quality-control outcomes, and historical process records. Subject to data quality, retention, synchronization, and analytical controls, these data may support monitoring, preventive-maintenance analysis, process optimization, and root-cause investigation. The database should therefore be treated as enabling infrastructure for proposed data-driven control and continuous-improvement activities, not as evidence that those outcomes will occur.

The strategic advantage of using an Edge Database is therefore its expected ability to combine low-latency access, scalability, offline operation, and efficient synchronization. These properties could support the improved solutions network by keeping secure HF-RFID/NFC credential events, project-identifier scans, machine states, and inspection outputs available where they are needed, while remaining compatible with broader enterprise-level data architectures.

5.1.4. Expected Advantages of Using Edge Computer Vision

Edge Computer Vision could strengthen the proposed network by processing selected visual data at or near the production line. If the edge devices provide sufficient processing capability, visual information could be analyzed locally instead of transferring all images or video streams to a remote server. This architecture is expected to reduce network dependence and may lower latency and bandwidth requirements, but the magnitude of any improvement must be established with the final model, image resolution, hardware, and plant network.

For manufacturing applications, local processing may be relevant for object detection, image classification, feature extraction, and anomaly detection. These techniques could be configured to identify parts, assess selected dimensions or surface characteristics, and flag suspected assembly deviations or nonconformities. When executed at the edge, they may provide timely feedback to operators and control systems, subject to demonstrated inference time, measurement capability, detection accuracy, and acceptable false-alarm rates.

A further expected benefit is reduced dependence on continuous cloud connectivity. If models, dependencies, storage, and decision logic are available locally, inspection tasks could continue during some network outages. In production scenarios where delayed defect detection may result in rework, material losses, or interruptions in downstream operations, it is essential that inspection and detection tasks continue locally. Therefore, edge-based visual inspection supports operational continuity and quality assurance.

Edge Computer Vision may also improve data privacy and efficiency. The complete visual stream does not have to be continuously transmitted outside the local environment.Sensitive production data can remain closer to the source. Only selected results, alerts, or summary information may be forwarded to the edge database, the manufacturing execution system, or the cloud platform. This may reduce data-transfer costs while preserving the information needed for traceability and analysis.

Within the improved solutions network, Edge Computer Vision could therefore serve as an automated quality-control component. By comparing machined parts with reference drawings or expected visual patterns, the system is expected to identify deviations earlier and provide operators with actionable information. This may support faster corrective action, reduce the risk of defective parts progressing through the process, and contribute to a more responsive and intelligent manufacturing environment.

5.2. Socio-Technical Barriers, Scaling Constraints, and Future Research

One limitation of this study is that the proposed improvements to the I4.0 solutions network have not yet been implemented in a company due to a lack of appropriate resources, which prevents the actual impact of the solution from being assessed. Implementing the I4.0 solutions network in a real production context therefore represents an appropriate next step for validating its effectiveness. Comparing production time, worker efficiency, production costs, and nonconformity occurrences before and after implementation would enable a more reliable evaluation of the proposed solution and help identify further improvement opportunities.

However, even the reference holistic proposal model [9]was carefully designed in the context and working methodologies of a specific company, which means that its implementation in other organizations may require certain adaptations.While shopfloor organization adapts to operational

and structural shifts, the underlying manufacturing technology often relies on the same universal engineering principles.

These research efforts focus on a specific stage of the production process, namely the machining of parts. However, the subsequent phases of the production process for this type of equipment, such as assembly and electrification, could also benefit from research into the implementation of I4.0-based solutions.

6. CONCLUSION

The main objective of this study was to contribute to the planning of an I4.0 solutions network that is compatible with different companies and applicable across a wide range of industries, especially in highly customized production contexts. To this end, a reference holistic proposal model for the production process of a company manufacturing cable harness testing equipment was studied to identify optimization opportunities and gaps that could be addressed through I4.0 technologies. The baseline network in [9] uses an unspecified RFID card, a worksheet QR Code, a centralized company database, and a CVS. The qualified proposal does not treat NFC as a separate replacement for RFID but specifies a secure 13.56 MHz HF-RFID/NFC credential profile. It adopts Data Matrix for the worksheet if compactness, quiet-zone, scanner-compatibility, or standards-adoption tests justify the change, and it proposes verified direct part marking when lifecycle traceability is required. The edge database and edge computer vision remain proposed architectural changes. The seven-stage network is expected to support more reliable and timely machining activities, but reductions in production time and defects have not been demonstrated and require empirical validation.

The proposed interconnection is now defined as a layered edge-to-enterprise architecture rather than a generic wireless hub: industrial Wi-Fi 6 supports mobile and non-critical traffic, wired industrial Ethernet carries high-bandwidth vision and machine connections, and private 5G remains an alternative for deployments that require qualified mobility or service-level control. OPC UA, MQTT 5.0, and IDTA AAS APIs provide the proposed device, event, and semantic interfaces. Edge nodes receive signed, hashed, read-only released packages and record the exact executed revision. These architectural controls are design requirements to be validated through failover, bandwidth, latency, and recovery testing. The resulting event data could later be analyzed using statistical or artificial-intelligence-based methodsin order to identify specific situations of nonconformity or inefficiency, leading to the identification of their causes, among other information that could be useful to the company.

6.1. Theoretical Implications and Architectural Contributions

The primary contribution of this study lies in refining the I4.0 reference conceptual model for the production of cable harness testing equipment through edge-oriented technologies and more precisely specified identification mechanisms. The proposed model replaces an unspecified RFID implementation with a defined secure 13.56 MHz HF-RFID/NFC credential. It also proposes Data Matrix in place of a worksheet QR Code where compactness or standards adoption is demonstrated, while identifying direct part marking as the stronger option when lifecycle traceability is required. Furthermore, the architecture introduces edge-computing principles by moving data storage and computer-vision processing from centralized infrastructure to edge nodes in the production environment. This shift is expected to reduce system latency, increase operational reliability, and improve the scalability of automated processes. The proposed identification and edge-processing choices remain hypotheses to be validated through site-specific security, readability, latency, and cost testing.

6.2. Architectural Trajectories and Edge-Cloud Evolution

Emerging paradigm shifts in enterprise software architecture indicate a transition toward distributed infrastructure. Industrial projections indicate that by 2030, approximately three-quarters of manufacturing organizations will deploy or modernize cloud-based Manufacturing Execution Systems (MES) within an end-to-end hybrid architecture, representing a near-doubling from the 2025 baseline [29]. This accelerating cloud migration within the MES domain is driving automation suppliers to prioritize web-accessible, cloud-native frameworks to support enterprise scalability [30]. Concurrently, localized edge computing architectures are increasingly deployed to alleviate cloud-connectivity vulnerabilities, data bottlenecks, and latency constraints. For this reason, manufacturing leaders will need to consider the cloud with edge components when building new production facilities or planning system upgrades.

This alignment with global edge-cloud integration trends supports the conceptual relevance of the proposed reference model. Practitioners could use this framework as a foundational template for highly customized, data-intensive industrial applications, subject to empirical validation and adaptation to the specific production context.

REFERENCES

[1] Bi, Z., Pomalaza-Ráez, C., Hershberger, D., Dawson, J., Lehman, A., Yurek, J., & Ball, J. (2018). Automation of Electrical Cable Harnesses Testing. *Robotics*, *7*(1), 1. https://doi.org/10.3390/robotics7010001

[2] Filip, D., Filip, L., Ucenic, C., Popan, A. I., &Avornicului, M.-C. (2026). A Data-Centric Architecture for Smart Cable Harness Assembly: 100% Continuity Testing, Pin-to-Pin Miswiring Diagnosis, Productivity Improvement, and Achieving Zero Customer Defects. *Applied Sciences*, *16*(9), 4281. https://doi.org/10.3390/app16094281

[3] Khouri, P. M. P., Walsh, M. J., Brandl, C., &Rybachuk, M. (2021). Design and automation of electrical cable harnesses testing system.*Microelectronics Reliability*, vol. 120, p. 114097.https://doi.org/10.1016/j.microrel.2021.114097

[4] International Electrotechnical Commission [IEC]. (2017). *IEC PAS 63088:2017 – Smart Manufacturing: Reference Architecture Model Industry 4.0 (RAMI 4.0)*.https://standards.iteh.ai/catalog/standards/iec/92492f13-9dc4-423c-b4d7-d280d0642ede/iec-pas-63088-2017

[5] Industrial Digital Twin Association [IDTA]. (2025). *Specification of the Asset Administration Shell – Part 1: Metamodel* (IDTA No. 01001-3-0-2). Plattform Industrie 4.0.https://industrialdigitaltwin.org/en/content-hub/aasspecifications/specification-of-the-asset-administration-shell-part-1-metamodel-idta-number-01001

[6] Siemens Digital Industries Software. (2021). *Model-based engineering for wire harness manufacturing* (White Paper). SiemensAG.https://www.plm.automation.siemens.com/media/global/es/Siemens_SW_Model_based_engineering_for_wire_harness_manufacturing_wp_tcm54-62596.pdf

[7] International Electrotechnical Commission [IEC]. (2013). *IEC 62264-1:2013: Enterprise-control system integration – Part 1: Models and terminology* (3rd ed.).https://cdn.standards.iteh.ai/samples/16715/d49a9bbae3d54b639880eeb8ef21b8e8/IEC-62264-1-2013.pdf

[8] Williams, T. J. (1994). The Purdue Enterprise Reference Architecture. *Computers in Industry*, *24*(2-3), 141–158. https://doi.org/10.1016/0166-3615(94)90017-5

[9] Rosa, E.S., Godina, R., Rodrigues, E.M.G., & Matias, J.C.O. (2022). An Industry 4.0 Conceptual Model Proposal for Cable Harness Testing Equipment Industry.*Procedia Computer Science*, vol. 200, pp. 1392–1401.https://doi.org/10.1016/j.procs.2022.01.340

[10] NXP Semiconductors [NXP]. 2024. *MIFARE DESFire EV3 contactless multi-application IC*. https://www.nxp.com/docs/en/data-sheet/MF3D_H_X3_SDS.pdf

[11] International Organization for Standardization [ISO]. (2024). *ISO/IEC 16022:2024 – Information technology – Automatic identification and data capture techniques – Data Matrix bar code symbology specification*. https://www.iso.org/standard/80926.html

[12] International Organization for Standardization [ISO]. (2024). *ISO/IEC 18004:2024 – Information technology – Automatic identification and data capture techniques – QR code bar code symbology specification*. https://www.iso.org/standard/83389.html

[13] H. Zhang et al. (2023). How Far Have Edge Clouds Gone? A Spatial-Temporal Analysis of Edge Network Latency In the Wild. *2023 IEEE/ACM 31st International Symposium on Quality of Service (IWQoS)*, Orlando, FL, USA, 2023, pp. 1-10.https://doi.org/10.1109/IWQoS57198.2023.10188741

[14] NVIDIA. (2026). *Jetson Orin Nano Super Developer Kit*. https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-orin/nano-super-developer-kit/

[15] Al-Ofeishat, H. A., & Al-Rababah, M. A. A. (2012). Near field communication (NFC). *International Journal of Computer Science and Network Security*, 12(2), 93–99. http://paper.ijcsns.org/07_book/201202/20120216.pdf

[16] National Institute of Standards and Technology [NIST]. (2022). *LPN-12: NFC Relay Man-in-the-Middle*, Mobile Threat Catalogue. https://pages.nist.gov/mobile-threat-catalogue/lan-pan-threats/LPN-12.html

[17] GS1. (2018). *DataMatrix Guideline: Overview and technical introduction to the use of GS1 DataMatrix*, Release 2.5.1, Ratified, Jan 2018; see also SAE AS9132 and MIL-STD-130 for direct-part-marking applications. https://www.gs1.org/docs/barcodes/GS1_DataMatrix_Guideline.pdf

[18] Abbas, N., Zhang, Y., Taherkordi, A., & Skeie, T. (2018). Mobile Edge Computing: A Survey. *IEEE Internet of Things Journal*, 5(1), pp. 450–465.https://doi.org/10.1109/jiot.2017.2750180

[19] Satyanarayanan, M. (2017). The Emergence of Edge Computing. *Computer*, 50(1), pp. 30–39.https://doi.org/10.1109/MC.2017.9

[20] Shi, W., &Dustdar, S. (2016). The Promise of Edge Computing, *Computer*, 49(5), pp. 78–81.https://doi.org/10.1109/MC.2016.145

[21] Ferreira, L. M. M., Coelho, F., & Pereira, J. (2024). Databases in Edge and Fog Environments: A Survey. *ACM Comput. Surv.* 56, 11, Article 285, 40 pages. https://doi.org/10.1145/3666001

[22] Azure Architecture Center. (2023). *End-to-end computer vision at the edge for manufacturing.* Microsoft Learn. https://web.archive.org/web/20240416080037/https://learn.microsoft.com/en-us/azure/architecture/reference-architectures/ai/end-to-end-smart-factory

[23] Deepchecks. (2022). Edge deployment using specialized camera [Diagram]. In *Best Practices for Computer Vision Model Deployment*. https://deepchecks.com/best-practices-for-computer-vision-model-deployment/

[24] Mahnke, W., & Leitner, S.-H. 2009. OPC Unified Architecture – The future standard for communication and information modeling in automation. *ABB Review* 3/2009, pp. 56-61. https://library.e.abb.com/public/75d70c47268d78bfc125762d00481f78/56-61%203M903_ENG72dpi.pdf

[25] OASIS Open. (2019). *MQTT Version 5.0*, OASIS Standard. https://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html

[26] Industrial Digital Twin Association [IDTA]. (2026). *Specification of the Asset Administration Shell – Part 2: Application Programming Interfaces*, IDTA-01002, Version 3.2. https://industrialdigitaltwin.org/en/wp-content/uploads/sites/2/2026/07/IDTA-01002-3-2_SpecificationAssetAdministrationShell_Part2_API.pdf

[27] Teledyne FLIR. (2026). *Allocating Bandwidth for a GigE Vision Camera*. https://softwareservices.flir.com/BFS-PGE-23S6/latest/40-Installation/AllocatingBandwidth.htm

[28] NFCForum. (2025). *NFC Release 15: The what, why and how*. https://nfc-forum.org/news/2025-06-nfc-release-15-the-what-why-and-how/

[29] Cunningham J., & Hestermann, C. (2025).*Market Guide for Manufacturing Execution Systems*. Gartner Research.https://www.gartner.com/en/documents/6420807

[30] Mitrevski, F., &Mitrevski, P. (2019). A Case Study of Productivity Improvement by using Cloud-based Process Planning Tools.In Ö. Çınar (Ed.), *Book of Proceedings of the 5th ICENS International Conference on Engineering and Natural Science*(pp. 380–386). CNR GROUP Publishing. https://doi.org/10.5281/zenodo.23047466

AUTHORS



Filip Mitrevski holds an MSc degree in Industrial Engineering and Management from the Faculty of Technical Sciences, University "St. Kliment Ohridski" – Bitola, and an MSc degree in Computer Science from the University of Skopje, North Macedonia. He also earned his BSc degree in Computer Science and Engineering from the Faculty of Information and Communication Technologies – Bitola. Professionally, he serves as an IE Global Specialist in Central Process Care at Kromberg & Schubert GmbH. His expertise and research interests encompass industrial management, lean manufacturing principles, process optimization, automotive engineering, vehicular networks, and cloud computing. He has co-authored several scientific papers at international conferences and holds multiple professional certifications.



Pece Mitrevski received his BSc and MSc degrees in Electrical and Computer Engineering, and the PhD degree in Computer Science from the "Ss. Cyril and Methodius" University – Skopje, North Macedonia. He is a Full Professor at the Faculty of Information and Communication Technologies, University "St. Kliment Ohridski" – Bitola, North Macedonia. His research interests include computer architecture, computer networks, cloud computing, performance and reliability analysis of computer systems, electronic business, digital transformation, and cybersecurity. He has authored over 130 publications in reputable journals and refereed conference proceedings and has delivered numerous lectures on these subjects. He is a member of both the IEEE Computer Society and the Association for Computing Machinery.



Silvana Angelevska is a Full Professor at the Faculty of Technical Sciences, University "St. Kliment Ohridski" – Bitola, North Macedonia. She earned her PhD in Technical Sciences from the same institution, where she has been a faculty member since 1993 and was elected Full Professor in 2017. Her primary academic expertise and research focus heavily on industrial management, maintenance management, quality management, strategic management, and project management. Her work also covers quality control systems and condition-based maintenance strategies in industrial facilities. Throughout her career, she has authored numerous scientific papers, mentored postgraduate research, and participated in various industrial and academic projects.