Requirement Specification Document: Light-Out Factory Platform

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**Location Context:** Ghaziabad, Uttar Pradesh, India

# **1. Introduction**

## 1.1 Purpose

This document outlines the complete requirements specification for a candidate "Light-Out Factory Platform." This platform aims to achieve a high degree of automation in manufacturing processes, minimizing or eliminating the need for human intervention during routine operations. This document serves as a blueprint for the design, development, and implementation of the platform.

## Business Values

* Simulate and model the behaviour i.e what-if scenarios.
* Impact of aggregated processes functions/machines etc

## 1.2 Scope

This document covers all functional and non-functional requirements for the Light-Out Factory Platform. This includes requirements related to:

* Automated production processes (e.g., assembly, machining, material handling).
* Automated material storage and retrieval.
* Quality control and inspection.
* Monitoring and control systems.
* Data acquisition, analysis, and reporting.
* System integration and interoperability.
* Security and safety.
* Maintenance and diagnostics.
* Scalability and flexibility.

This document does not cover the specific details of the products being manufactured, but rather the underlying platform capabilities to support automated manufacturing.

## 1.3 Intended Audience

This document is intended for the following stakeholders:

* Project Managers
* System Architects
* Software Development Teams
* Hardware Engineering Teams
* Automation Engineers
* Quality Assurance Teams
* Operations and Maintenance Personnel
* Business Stakeholders

## 1.4 Definitions and Acronyms

|  |  |
| --- | --- |
| **Term/Acronym** | **Definition** |
| AMR | Autonomous Mobile Robot |
| AGV | Automated Guided Vehicle |
| AS/RS | Automated Storage and Retrieval System |
| CNC | Computer Numerical Control |
| ERP | Enterprise Resource Planning |
| IIoT | Industrial Internet of Things |
| MES | Manufacturing Execution System |
| PLC | Programmable Logic Controller |
| AI | Artificial Intelligence |
| ML | Machine Learning |
| HMI | Human-Machine Interface |
| KPI | Key Performance Indicator |
| API | Application Programming Interface |
| RFID | Radio-Frequency Identification |
| OEE | Overall Equipment Effectiveness |
| SCADA | Supervisory Control and Data Acquisition |
| WMS | Warehouse Management System |
| CPS | Cyber-Physical System |

# **2. Overall Description**

## 2.1 Product Perspective

The Light-Out Factory Platform will be a comprehensive and integrated system encompassing hardware, software, and network infrastructure to automate manufacturing operations. It will interact with existing enterprise systems (e.g., ERP, WMS) for order management, inventory control, and shipping. The platform will be designed for minimal human intervention during production, relying on robots, automated machinery, sensors, and intelligent control systems.

## 2.2 Product Functions

The platform will provide the following core functions:

* **Automated Production Execution:** Executing manufacturing processes based on predefined instructions and schedules, including material processing, assembly, and finishing.
* **Automated Material Handling:** Receiving, storing, retrieving, and transporting raw materials, components, and finished goods within the factory using AMRs, AGVs, and AS/RS.
* **Automated Quality Control:** Performing in-process and final product quality checks using vision systems, sensors, and other automated inspection technologies.
* **Real-time Monitoring and Control:** Providing a centralized interface for monitoring the status of all automated equipment, processes, and environmental conditions. Allowing for remote adjustments and interventions when necessary.
* **Data Acquisition and Analysis:** Collecting data from all connected devices and systems for performance monitoring, trend analysis, predictive maintenance, and process optimization.
* **Automated Maintenance and Diagnostics:** Monitoring equipment health, predicting potential failures, and providing diagnostic information to facilitate timely maintenance.
* **System Integration:** Seamlessly integrating with existing enterprise systems (ERP, WMS) and other relevant platforms.
* **Security Management:** Ensuring the security and integrity of the platform and its data.
* **Safety Management:** Implementing automated safety protocols and monitoring systems to prevent accidents.

## 2.3 User Characteristics

While the goal is minimal human intervention in production, certain roles will interact with the platform:

* **System Administrators:** Responsible for platform setup, configuration, user management, and overall system health. Requires strong IT and automation knowledge.
* **Maintenance Technicians:** Responsible for maintaining and repairing automated equipment. Will use the platform for diagnostics and scheduling maintenance. Requires expertise in robotics, mechanics, and electronics.
* **Process Engineers:** Responsible for designing and optimizing manufacturing processes. Will use the platform's data analysis tools to identify areas for improvement. Requires strong understanding of manufacturing processes and data analytics.
* **Supervisors (Limited Interaction):** May occasionally monitor overall production performance and intervene in exceptional circumstances through the centralized interface. Requires a high-level understanding of the automated processes.

## 2.4 Operating Environment

The platform will operate within a factory environment in Ghaziabad, Uttar Pradesh, India. This environment may present challenges such as:

* Fluctuations in ambient temperature and humidity.
* Potential for dust and other airborne particles.
* Specific power supply characteristics.
* Network connectivity requirements and potential limitations.
* Integration with existing legacy systems.
* Adherence to local safety regulations and standards.

## 2.5 Design and Implementation Constraints

The design and implementation of the platform must adhere to the following constraints:

* **Budgetary Constraints:** The project must be implemented within a defined budget.
* **Timeline Constraints:** Specific milestones and a final implementation deadline will need to be met.
* **Regulatory Compliance:** The platform must comply with all relevant local and national regulations, including safety and environmental standards.
* **Integration with Existing Systems:** The platform must seamlessly integrate with specified existing ERP, WMS, and other relevant systems.
* **Scalability Requirements:** The platform should be designed to accommodate future expansion and increased production volumes.
* **Reliability and Uptime Requirements:** The platform must be highly reliable with minimal downtime.
* **Security Requirements:** Robust security measures must be implemented to protect the platform and its data.
* **Maintainability Requirements:** The platform should be designed for ease of maintenance and upgrades.
* **Local Resource Availability:** Consideration should be given to the availability of skilled personnel for implementation and maintenance in the Ghaziabad region.

## 2.6 Assumptions

The following assumptions are made during the creation of this document:

* Reliable power supply will be available at the factory location.
* A suitable network infrastructure will be in place or will be developed to support the platform's communication requirements.
* Necessary data interfaces and APIs will be available for integration with existing enterprise systems.
* Standard industrial communication protocols (e.g., OPC UA, MQTT) will be supported by the chosen hardware and software components.
* Adequate training will be provided to personnel interacting with the platform.

# **3. Specific Requirements**

## 3.1 Functional Requirements

### **3.1.1 Automated Production Execution (PROD)**

* **PROD-001:** The system shall be able to receive production orders from the MES.
* **PROD-002:** The system shall be able to translate production orders into executable tasks for automated equipment (robots, CNC machines, etc.). For list of standard protocols refer to Appendix.
* **PROD-003:** The system shall be able to control and coordinate the operation of multiple automated machines simultaneously.
* **PROD-004:** The system shall be able to track the progress of each production order in real-time.
* **PROD-005:** The system shall be able to manage and optimize production schedules based on resource availability and priorities.
* **PROD-006:** The system shall be able to handle variations in product configurations and recipes.
* **PROD-007:** The system shall be able to automatically adjust process parameters based on sensor feedback and quality control data.
* **PROD-008:** The system shall be able to pause and resume production processes automatically or through remote commands.
* **PROD-009:** The system shall be able to handle exceptions and errors during production and trigger appropriate alerts.
* **PROD-010:** The system shall be able to generate production reports, including cycle times, output quantities, and resource utilization.

### **3.1.2 Automated Material Handling (MHL)**

* **MHL-001:** The system shall be able to receive instructions for material movement from the MES and WMS.
* **MHL-002:** The system shall be able to control AMRs and AGVs for transporting materials between designated locations (e.g., storage, workstations, shipping).
* **MHL-003:** The system shall be able to manage the operation of the AS/RS for automated storage and retrieval of materials.
* **MHL-004:** The system shall be able to track the location and status of all materials in real-time using RFID or other tracking technologies.
* **MHL-005:** The system shall be able to optimize material flow to minimize transportation times and bottlenecks.
* **MHL-006:** The system shall be able to handle different types and sizes of materials.
* **MHL-007:** The system shall be able to automatically verify the correct materials are being transported to the correct locations.
* **MHL-008:** The system shall be able to manage inventory levels within the automated storage areas.
* **MHL-009:** The system shall be able to generate reports on material handling efficiency and inventory levels.

### **3.1.3 Automated Quality Control (QC)**

* **QC-001:** The system shall be able to integrate with automated inspection devices (e.g., vision systems, coordinate measuring machines (CMMs), sensors).
* **QC-002:** The system shall be able to execute automated quality checks at predefined stages of the production process.
* **QC-003:** The system shall be able to compare inspection data against predefined quality standards and tolerances.
* **QC-004:** The system shall be able to automatically identify and flag non-conforming products.
* **QC-005:** The system shall be able to trigger automated actions based on quality control results (e.g., reject defective parts, pause production).
* **QC-006:** The system shall be able to store and manage quality control data for traceability and analysis.
* **QC-007:** The system shall be able to generate quality control reports, including defect rates and trends.
* **QC-008:** The system shall support remote configuration and calibration of automated inspection devices.

### **3.1.4 Real-time Monitoring and Control (MON)**

* **MON-001:** The system shall provide a centralized, real-time visual overview of the status of all automated equipment and processes.
* **MON-002:** The system shall display key performance indicators (KPIs) such as OEE, cycle time, and production output.
* **MON-003:** The system shall provide real-time alerts and notifications for critical events, errors, and equipment malfunctions.
* **MON-004:** Authorized users shall be able to remotely monitor and control individual machines and processes.
* **MON-005:** The system shall log all significant events and operator actions.
* **MON-006:** The system shall provide historical data visualization and analysis capabilities.
* **MON-007:** The system shall allow for the creation of customized dashboards and reports.
* **MON-008:** The system shall support secure remote access for authorized personnel.

### **3.1.5 Data Acquisition and Analysis (DATA)**

* **DATA-001:** The system shall automatically collect data from all connected devices, sensors, and systems.
* **DATA-002:** The system shall store collected data in a structured and accessible format.
* **DATA-003:** The system shall provide tools for data analysis, trend identification, and root cause analysis.
* **DATA-004:** The system shall support the generation of customizable reports and visualizations.
* **DATA-005:** The system shall be able to integrate with AI/ML algorithms for predictive maintenance and process optimization.
* **DATA-006:** The system shall ensure data integrity and security.

### **3.1.6 Automated Maintenance and Diagnostics (MNT)**

* **MNT-001:** The system shall continuously monitor the health and performance of automated equipment based on sensor data.
* **MNT-002:** The system shall be able to predict potential equipment failures based on historical data and real-time analysis.
* **MNT-003:** The system shall generate alerts for potential maintenance needs.
* **MNT-004:** The system shall provide diagnostic information to assist maintenance technicians in troubleshooting issues.
* **MNT-005:** The system shall support the scheduling and tracking of maintenance activities.
* **MNT-006:** The system shall maintain a log of all maintenance activities performed.

### **3.1.7 System Integration (INT)**

* **INT-001:** The platform shall integrate seamlessly with the existing ERP system for receiving production orders and updating production status.
* **INT-002:** The platform shall integrate seamlessly with the existing WMS for managing material flow and inventory.
* **INT-003:** The platform shall support standard industrial communication protocols (e.g., OPC UA, MQTT) for communication with various automated devices.
* **INT-004:** The platform shall provide APIs for integration with future systems and applications.
* **INT-005:** The platform shall ensure secure data exchange with integrated systems.

### **3.1.8 Security Management (SEC)**

* **SEC-001:** The platform shall implement robust user authentication and authorization mechanisms.
* **SEC-002:** The platform shall encrypt sensitive data both in transit and at rest.
* **SEC-003:** The platform shall include mechanisms for detecting and preventing unauthorized access and cyber threats.
* **SEC-004:** The platform shall maintain audit logs of all system access and modifications.
* **SEC-005:** The platform shall adhere to relevant cybersecurity standards and best practices.

### **3.1.9 Safety Management (SAFE)**

* **SAFE-001:** The platform shall integrate with automated safety systems (e.g., light curtains, safety scanners, emergency stops).
* **SAFE-002:** The system shall monitor safety zones and trigger automatic shutdowns in case of intrusions.
* **SAFE-003:** The system shall log all safety-related events and alarms.
* **SAFE-004:** The platform shall support remote monitoring of safety system status.
* **SAFE-005:** The design and implementation shall comply with all relevant local and national safety regulations.

## 3.2 Non-Functional Requirements

### **3.2.1 Performance Requirements (PERF)**

* **PERF-001:** The system shall be able to process production orders from the MES within [Specify acceptable time, e.g., 5 seconds].
* **PERF-002:** Real-time monitoring data shall be updated on the central dashboard with a latency of no more than [Specify acceptable latency, e.g., 1 second].
* **PERF-003:** The system shall be able to handle [Specify expected data volume] of data per day without performance degradation.
* **PERF-004:** Automated material handling systems shall be able to complete transportation tasks within [Specify acceptable timeframes for different tasks].
* **PERF-005:** Automated quality checks shall be performed within [Specify acceptable time per check] without impacting production throughput.

### **3.2.2 Reliability Requirements (RELI)**

* **RELI-001:** The platform shall have an overall system uptime of at least [Specify percentage, e.g., 99.9%].
* **RELI-002:** Critical system components shall have built-in redundancy to minimize single points of failure.
* **RELI-003:** The system shall have automated mechanisms for error detection and recovery.
* **RELI-004:** Data loss in case of system failure shall be minimized to [Specify acceptable data loss window, e.g., no data loss].

### **3.2.3 Usability Requirements (USAB)**

* **USAB-001:** The centralized monitoring and control interface shall be intuitive and easy to navigate for authorized users.
* **USAB-002:** System alerts and notifications shall be clear, concise, and actionable.
* **USAB-003:** The system shall provide adequate online help and documentation.
* **USAB-004:** Data visualization tools shall be user-friendly and allow for customization.

### **3.2.4 Maintainability Requirements (MNTN)**

* **MNTN-001:** The platform shall be designed for modularity to facilitate easy maintenance and upgrades of individual components.
* **MNTN-002:** System logs and diagnostic information shall be comprehensive and easily accessible.
* **MNTN-003:** Software updates and patches shall be deployable with minimal disruption to ongoing operations.
* **MNTN-004:** The platform shall provide remote diagnostic capabilities.

### **3.2.5 Portability Requirements (PORT)**

* **PORT-001:** While primarily intended for the current factory location, the software components of the platform should be designed with consideration for potential future deployment in other locations with similar infrastructure. [This may be less critical for a highly integrated hardware-software platform but consider software dependencies].

### **3.2.6 Scalability Requirements (SCAL) (Continued)**

* **SCAL-003:** The software components of the platform should be able to scale horizontally to handle increased processing loads.

## 3.3 External Interface Requirements

### **3.3.1 User Interfaces**

* **UI-001:** The platform shall provide a secure, web-based graphical user interface (GUI) for system administrators, maintenance technicians, and process engineers.
* **UI-002:** The GUI shall provide real-time dashboards displaying key operational metrics and system status.
* **UI-003:** The GUI shall allow authorized users to monitor and control automated equipment remotely.
* **UI-004:** The GUI shall provide tools for data visualization, analysis, and reporting.
* **UI-005:** The GUI shall support role-based access control.

### **3.3.2 Hardware Interfaces**

* **HI-001:** The platform shall interface with various industrial robots using standard communication protocols (e.g., Ethernet/IP, PROFINET).
* **HI-002:** The platform shall interface with CNC machines using appropriate communication protocols (e.g., MTConnect, FANUC FOCAS).
* **HI-003:** The platform shall interface with AMRs and AGVs using their respective communication protocols and APIs.
* **HI-004:** The platform shall interface with the AS/RS control system.
* **HI-005:** The platform shall interface with various sensors (e.g., temperature, pressure, proximity, vision systems) using standard industrial protocols (e.g., Modbus, OPC UA).
* **HI-006:** The platform shall interface with automated safety devices (e.g., light curtains, safety scanners) using their designated interfaces.

### **3.3.3 Software Interfaces**

* **SI-001:** The platform shall integrate with the existing ERP system via APIs (e.g., RESTful APIs, SOAP).
* **SI-002:** The platform shall integrate with the existing WMS via APIs.
* **SI-003:** The platform shall support standard industrial communication protocols (e.g., OPC UA, MQTT) for data exchange with other systems.
* **SI-004:** The platform shall provide its own APIs to allow for integration with future applications and services.

### **3.3.4 Communication Interfaces**

* **CI-001:** The platform shall communicate over a secure industrial Ethernet network.
* **CI-002:** The platform shall support wireless communication protocols (e.g., Wi-Fi) for mobile devices and AMRs/AGVs, ensuring secure connectivity.
* **CI-003:** The platform shall support secure remote access for authorized personnel via VPN or other secure methods.

# **4. Data Requirements**

* **DATA-REQ-001:** The system shall collect and store real-time data from all automated equipment, sensors, and control systems.
* **DATA-REQ-002:** The system shall store historical data for analysis and reporting purposes for a period of [Specify retention period, e.g., 5 years].
* **DATA-REQ-003:** All collected data shall be timestamped and accurately recorded.
* **DATA-REQ-004:** The system shall ensure data integrity and prevent unauthorized modification.
* **DATA-REQ-005:** The data model shall be designed to facilitate efficient querying and analysis.
* **DATA-REQ-006:** The system shall support data export in common formats (e.g., CSV, Excel).
* **DATA-REQ-007:** The system shall manage different types of data, including sensor readings, machine status, production parameters, quality control results, and maintenance logs.

# **5. Security Requirements**

* **SEC-REQ-001:** All user access to the platform shall be authenticated using strong password policies and multi-factor authentication where appropriate.
* **SEC-REQ-002:** User roles and permissions shall be strictly defined and enforced based on the principle of least privilege.
* **SEC-REQ-003:** All sensitive data transmitted between components and external systems shall be encrypted using industry-standard encryption protocols (e.g., TLS/SSL).
* **SEC-REQ-004:** Data at rest shall be encrypted using appropriate encryption algorithms.
* **SEC-REQ-005:** The platform shall include intrusion detection and prevention mechanisms.
* **SEC-REQ-006:** Regular security audits and vulnerability assessments shall be conducted.
* **SEC-REQ-007:** The platform shall maintain comprehensive audit logs of all security-related events.
* **SEC-REQ-008:** Physical access to the platform's hardware infrastructure shall be restricted to authorized personnel.

# **6. Safety Requirements**

* **SAFE-REQ-001:** The platform shall integrate with and monitor the status of all automated safety systems (e.g., emergency stops, light curtains, safety scanners).
* **SAFE-REQ-002:** The system shall trigger automatic shutdowns of automated equipment in case of safety violations or detected hazards.
* **SAFE-REQ-003:** The platform shall provide real-time alerts for safety-related events and alarms.
* **SAFE-REQ-004:** The system shall maintain a log of all safety-related incidents and alarms.
* **SAFE-REQ-005:** The design and implementation of the platform shall adhere to all relevant local and national safety regulations and standards (specific standards to be identified based on the location and industry).
* **SAFE-REQ-006:** The platform shall support remote monitoring of the status of safety systems.
* **SAFE-REQ-007:** Procedures for manual override of automated systems in emergency situations shall be clearly defined and implemented with appropriate safety interlocks.

# **7. Maintenance and Support Requirements**

* **MNT-SUPP-001:** The platform shall provide comprehensive diagnostic tools for identifying and troubleshooting system issues.
* **MNT-SUPP-002:** The system shall support remote access for authorized maintenance personnel.
* **MNT-SUPP-003:** The platform shall generate alerts for potential equipment failures based on predictive maintenance algorithms.
* **MNT-SUPP-004:** The system shall facilitate the scheduling and tracking of maintenance activities.
* **MNT-SUPP-005:** Comprehensive documentation, including system architecture, user manuals, and troubleshooting guides, shall be provided.
* **MNT-SUPP-006:** Provisions for remote software updates and patching shall be included.
* **MNT-SUPP-007:** Service level agreements (SLAs) for platform support and response times shall be defined.

# **8. Future Considerations (Non-Binding)**

* Integration with advanced AI/ML models for further process optimization and autonomous decision-making.
* Implementation of digital twin technology for simulation and virtual commissioning.
* Integration with augmented reality (AR) tools for remote maintenance and assistance.
* Expansion of the platform to support additional manufacturing processes.
* Consideration of energy monitoring and optimization features.

# **9. Appendix**

* Glossary of terms (already included in Section 1.4)
* List of relevant regulations and standards (to be populated based on specific industry and location details)
* Interface control documents (ICDs) for integration with external systems (to be developed during detailed design)

## Models

* Building Information Management (BIM)

## Taxonomy

* <https://www.wipro.com/engineering/a-digital-twin-taxonomy-for-industry-implementations/>

## Maturity Model Levels

We'll use a five-level model for each component:

* **Level 1: Basic/Reactive:** Initial implementation, primarily manual with some automation. Reactive to issues.
* **Level 2: Managed/Defined:** Processes are defined and documented. Basic monitoring and control in place.
* **Level 3: Integrated/Proactive:** Multiple components are integrated. Proactive monitoring and basic analytics are used.
* **Level 4: Intelligent/Optimized:** AI/ML and advanced analytics are used for optimization and prediction. Minimal human intervention in routine tasks.
* **Level 5: Autonomous/Light-Out:** Fully automated, self-optimizing, and self-healing with near-zero human intervention.

### **Maturity States by Component:**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Component** | **Level 1: Basic/Reactive** | **Level 2: Managed/Defined** | **Level 3: Integrated/Proactive** | **Level 4: Intelligent/Optimized** | **Level 5: Autonomous/Light-Out** |
| **Automated Production Execution** | Standalone automated machines; manual loading/unloading. | Defined programs for automated tasks; basic HMI monitoring. | Integrated control of multiple machines via MES; real-time status tracking. | AI-powered process optimization; adaptive parameter adjustments; automated error correction. | Fully autonomous production; self-configuration for different product variations; predictive quality control. |
| **Automated Material Handling** | Manual transport with some AGVs for fixed routes. | Defined routes for AGVs; basic inventory tracking. | Integrated AMR/AGV fleet managed by MES/WMS; dynamic route planning. | AI-driven optimized material flow; predictive maintenance of transport systems; autonomous inventory management. | Fully autonomous material flow; self-organizing storage and retrieval; zero human intervention in logistics. |
| **Automated Quality Control** | Manual inspections with some standalone automated checks. | Defined QC procedures; automated checks at specific points; data logging. | Integrated QC data with production data; real-time alerts for deviations. | AI-powered advanced defect detection; predictive quality analysis; automated process adjustments based on QC. | Fully autonomous quality assurance; self-calibrating inspection systems; zero-defect manufacturing. |
| **Real-time Monitoring & Control** | Isolated machine HMIs; manual data collection. | Centralized SCADA/MES for basic monitoring; manual data logging. | Integrated platform providing real-time visibility across all systems; automated KPI tracking. | AI-powered anomaly detection; predictive alerts; automated remote adjustments and control. | Fully autonomous monitoring and control; self-diagnostics and automated resolution of issues. |
| **Data Acquisition & Analysis** | Manual data collection and basic spreadsheets. | Centralized data storage; predefined reports; basic trend analysis. | Integrated data from all systems; automated report generation; proactive alerts based on thresholds. | AI/ML-powered predictive analytics; process optimization recommendations; automated anomaly investigation. | Fully autonomous data-driven decision making; self-optimizing processes based on real-time data analysis. |
| **Automated Maintenance & Diagnostics** | Reactive maintenance based on failures. | Scheduled preventative maintenance; basic equipment monitoring. | Integrated equipment health monitoring; automated logging of maintenance activities. | AI/ML-powered predictive maintenance; automated diagnostics and recommended actions; remote repair capabilities. | Fully autonomous maintenance; self-repairing systems; proactive component replacement based on predicted lifespan. |
| **System Integration** | Point-to-point integrations; manual data exchange. | Defined interfaces between key systems (ERP, WMS, MES). | Seamless data exchange between all platform components and enterprise systems via APIs. | AI-powered intelligent integration; automated data mapping and transformation; self-healing integration links. | Fully autonomous and dynamic system integration; plug-and-play integration of new components. |
| **Security Management** | Basic password protection; isolated security measures. | Defined security policies; centralized user management; basic firewalls. | Integrated security monitoring; intrusion detection systems; data encryption in transit. | AI-powered threat detection and prevention; automated security patching and updates; adaptive security measures. | Fully autonomous security management; self-monitoring and self-healing security infrastructure. |
| **Safety Management** | Physical safety barriers and manual emergency stops. | Basic safety sensors and interlocks; defined safety procedures. | Integrated safety systems monitored centrally; automated safety zone enforcement. | AI-powered real-time hazard detection; predictive safety risk assessment; automated safety interventions. | Fully autonomous safety management; self-monitoring and self-enforcing safety protocols; proactive risk mitigation. |

## Examples of Companies with Significant Lights-Out Operations or Platforms:

* **FANUC (Japan):** A leading robotics company, FANUC famously operates a "lights-out" factory where robots build other robots with minimal human intervention, capable of running unsupervised for extended periods (reports suggest up to 30 days).
* **Philips (Netherlands):** Uses a highly automated factory with around 128 robots to produce electric razors, with only a handful of human workers for final quality assurance.
* **Siemens (Germany):** Their Amberg plant has a very high degree of automation (around 75%), achieving a near-perfect quality rate with minimal human involvement in the core production processes of programmable logic controllers (PLCs).
* **Foxconn (China):** Has implemented "lights-off" factories, particularly in Shenzhen, for producing electronic equipment components like smartphones, utilizing extensive robotics, AI for optimization, and automated quality control.
* **Tesla (USA):** While not entirely "lights-out," Tesla's Gigafactories heavily emphasize automation in vehicle and battery production, with a stated long-term goal of fully autonomous production.
* **Amazon (Global):** While primarily focused on logistics and warehousing, Amazon utilizes extensive robotic systems in its fulfilment centres with minimal human intervention in many sorting and movement tasks.
* **Various CNC Machining Facilities:** Many CNC machining shops are implementing "lights-out" or "lights-sparse" operations for unattended machining during nights and weekends.
* **Micro-factories utilizing Additive Manufacturing:** Some smaller, specialized manufacturing firms using 3D printing are achieving near "lights-out" operation, especially when combined with automated part harvesting.

## Key Characteristics and Trends:

* **Focus on Specific Industries and Processes:** Fully lights-out operations are more common in industries with highly standardized products and repetitive processes, such as electronics manufacturing, automotive component production, and certain types of machining.
* **Gradual Implementation:** Most companies are adopting automation incrementally, starting with specific cells or processes and gradually expanding towards a more lights-out model.
* **Hybrid Models are Common:** Many facilities operate with a "lights-sparse" approach, where automation handles the bulk of production, but some human presence is still required for setup, maintenance, complex problem-solving, and quality assurance.
* **Technology Enablers are Maturing:** The increasing sophistication and affordability of industrial robots, AI, machine vision, IIoT, and advanced control systems are making more extensive lights-out operations feasible.
* **Regional Differences:** Adoption rates and specific examples might vary geographically, with some reports suggesting a strong push in Asia (especially China) and increasing interest in Western countries due to labor costs and efficiency drives.

## Industrial Communication Protocols

| **Protocol** | **Type / Layer** | **Medium** | **Typical Use Case** | **Vendors / Systems** |
| --- | --- | --- | --- | --- |
| **Modbus RTU** | Fieldbus | Serial (RS-232/485) | PLCs, sensors, CNCs | Schneider, Siemens, etc. |
| **Modbus TCP** | Ethernet-based Fieldbus | Ethernet | Same as above, but over Ethernet | Widely supported |
| **PROFIBUS** | Fieldbus | RS-485 | General automation, I/O devices | Siemens, Bosch Rexroth |
| **PROFINET** | Ethernet-based Fieldbus | Ethernet | Factory automation, robotics | Siemens, Festo |
| **EtherNet/IP** | Ethernet-based Fieldbus | Ethernet | Machine control, I/O, PLCs | Rockwell Automation (Allen-Bradley) |
| **DeviceNet** | Fieldbus | CAN | Sensors, actuators, I/O | Allen-Bradley, Omron |
| **CANopen** | Fieldbus | CAN | Robotics, embedded automation | Bosch, KUKA |
| **CC-Link** | Fieldbus | RS-485 / Ethernet | Machine & process automation | Mitsubishi Electric |
| **EtherCAT** | Real-time Ethernet | Ethernet | High-speed motion, robotics | Beckhoff, B&R, Yaskawa |
| **Powerlink** | Real-time Ethernet | Ethernet | Motion control, deterministic networks | B&R, ABB |
| **SERCOS III** | Real-time Ethernet | Ethernet | Motion & CNC systems | Bosch Rexroth, Siemens |
| **MTConnect** | Monitoring / Analytics | Ethernet / HTTP | CNC data collection & analysis | Mazak, Okuma, FANUC |
| **FANUC FOCAS** | CNC-Specific API | Ethernet / Serial | FANUC CNC control, data collection | FANUC |
| **Heidenhain LSV2** | CNC Communication Protocol | Serial / Ethernet | Heidenhain CNCs, metrology | Heidenhain |
| **SINUMERIK OPC UA** | CNC Protocol / OPC | Ethernet | Siemens CNC integration | Siemens SINUMERIK |
| **OPC DA** | SCADA/HMI Protocol | COM/DCOM (Windows) | Classic Windows-based PLC/HMI | Many vendors |
| **OPC UA** | SCADA/HMI/IIoT | Ethernet | Modern, secure, platform-independent comms | Siemens, Rockwell, Beckhoff, etc. |
| **MQTT** | IIoT Protocol | TCP/IP (Ethernet/Wi-Fi) | Lightweight messaging for IIoT/cloud integration | SCADA, cloud services, gateways |
| **DNC** | CNC File Transfer | Serial / Ethernet | Sending NC programs to CNC machines | FANUC, Mazak, Siemens |
| **ADS (Beckhoff)** | PLC/CNC Integration | Ethernet / TwinCAT | Beckhoff controllers communication | Beckhoff |
| **AS-i** | Simple I/O Network | Special 2-wire | Sensors/actuators in low-level automation | Siemens, IFM, Pepperl+Fuchs |
| **INTERBUS** | Fieldbus | Serial (RS-485) | Sensors and actuators | Phoenix Contact |

| **Protocol** | **Transport Layer** | **Communication Model** | **Real-Time Capable** | **Open Source** | **Pub/Sub Native** | **Typical Use** |
| --- | --- | --- | --- | --- | --- | --- |
| **Modbus RTU** | RS-232 / RS-485 | Polling (Master-Slave) | ❌ | Yes | ❌ | Sensors, PLCs |
| **Modbus TCP** | Ethernet | Polling (Client-Server) | ❌ | Yes | ❌ | PLCs, SCADA |
| **PROFIBUS** | RS-485 | Polling / Cyclic | ✔️ (Soft real-time) | No | ❌ | General automation |
| **PROFINET** | Ethernet | Cyclic + Acyclic | ✔️ (with IRT) | No | ❌ | Siemens systems, robotics |
| **EtherNet/IP** | Ethernet | Cyclic / Implicit / Explicit | ✔️ | No | ❌ | Allen-Bradley, PLCs |
| **DeviceNet** | CAN | Polling / Cyclic | ✔️ | No | ❌ | Field I/O, small devices |
| **CANopen** | CAN | Event-driven / Polling | ✔️ | Yes | ❌ | Robotics, embedded control |
| **CC-Link** | RS-485 / Ethernet | Cyclic | ✔️ | No | ❌ | Mitsubishi automation |
| **EtherCAT** | Ethernet | Distributed Clock Sync | ✔️ (Hard real-time) | No | ❌ | High-speed motion, robotics |
| **Powerlink** | Ethernet | Time-scheduled (TDMA) | ✔️ (Hard real-time) | Yes | ❌ | Real-time robotics, motion control |
| **SERCOS III** | Ethernet | Cyclic / Deterministic | ✔️ (Hard real-time) | Yes | ❌ | Motion control, CNCs |
| **MTConnect** | HTTP/XML over Ethernet | Pull (Client polling) | ❌ | Yes | ❌ (Push via adapter) | CNC data collection |
| **FANUC FOCAS** | Ethernet / Serial | API Calls / Polling | ❌ | No | ❌ | FANUC CNC integration |
| **Heidenhain LSV2** | Serial / Ethernet | Serial Messaging | ❌ | No | ❌ | CNC, metrology |
| **SINUMERIK OPC UA** | Ethernet | Pub/Sub + Client/Server | ✔️ (via OPC UA PubSub) | Yes | ✔️ | Siemens CNC |
| **OPC DA** | COM/DCOM (Windows) | Client/Server (Polling) | ❌ | No | ❌ | Legacy SCADA |
| **OPC UA** | Ethernet | Client/Server + Pub/Sub | ✔️ | Yes | ✔️ | IIoT integration |
| **MQTT** | TCP/IP (Ethernet/Wi-Fi) | Pub/Sub | ❌ | Yes | ✔️ | IIoT / Cloud / SCADA |
| **ADS (Beckhoff)** | TCP/IP (TwinCAT) | Client/Server | ✔️ | Yes | ❌ | Beckhoff PLCs |
| **AS-i** | 2-wire special cable | Cyclic | ✔️ |  | ❌ | Low-level sensors/actuators |
| **DNC** | Serial / Ethernet | File Transfer (Polling) | ❌ | Yes | ❌ | CNC program upload/download |

# **Learning from Books**

**Reference: Building Industrial Digital Twins**

* + Modelling approach
    - Discrete DT ~ Component
    - Composite DT ~ entity
    - Digital Twin Prototype (DTP) ~ class of objects
    - Digital Twin Instance (DTI) ~ instance of class
    - Digital Twin Aggregate (DTA) ~ group/collection of instances of classes
    - Digital Thread ~ capture business process
    - DPI
    - DTPs and DTIs definition and configuration can be governed by JSON.
  + Models / Industrial models
    - Building Information Management (BIM) models
    - Computer Aided Design (CAD)
    - Augmented Reality (AR)
    - Virtual Reality (VR)
    - Geographic Information System (GIS)
    - Failure Mode and Effect Analysis (FMEA)
    - Root Cause Analysis (RCA)
  + Key capabilities
    - Cover Enter life cycle of products, processes & DT development cycle.
  + Mapping of multiple life cycles.

|  |  |  |  |
| --- | --- | --- | --- |
| **Life Cycles and Mapping & DT** | | | |
| Manufacturer | | Customer/User | |
| Design | Manufacture | Build/Integrate | Operate/Maintain |
| DTP | DTI, DTP | System Context, DTI, DTP | Operational Data, System Context, DTI, DTP |
| **Product Lifecycle Management (PLM) Physical Env** | | | |
| Physical Asset Instance | | Assembly | System |

* + DT relationships and types
    - DT single / Atomic entity
    - Composite DT assembly of DT discrete
    - Composite DT assembly of composite DT
  + Entities
    - Discrete DT is the lowest level of abstraction in a use case, where further breaking will not add any value. And it does not need to be broken down into further small parts.
  + Use Cases
    - DT of manufacturing product and monitor it’s use indicating failure, sub optimal performance.
    - DT providing insight into the operations, it’s composite DT.
    - Discrete DT, part of composite DT like assembly line.
    - DT in smart manufacturing
    - DT for simulation twin, operational twin (continuous) and Project simulation
    - Predict energy demand,
  + Capabilities
    - Physics based algo, historical data, real time data.
    - Analytics
    - Computational Fluid Dynamic (CFD)
    - finite element methods (FEM)
  + Characteristics
    - Pg: Chapter 1, pg 36
    - **Physical Entity (Physical Twin):** "An entity is an item that has recognizably distinct existence, e.g., a person, an organization, a device, a subsystem or a group of such items" (ISO/IEC 24760-1:2011)
    - **Physical Environment:** The real-world environment that the Physical Twin exists in (factory, oil platform, hospital, nature reserve, etc.)
    - **Virtual Entity (Virtual Twin):** The virtual Digital Twin prototype (DTP) and instance(s) synchronized with the physical entity at a twinning rate
    - **Virtual Environment:** The technology-based environment that the virtual Twin exists in
    - **Synchronization (twinning):** Synchronization or updating the state of the physical twin and virtual twin
    - **Twinning Rate:** The rate or frequency at which synchronization happens
    - **State:** The values of all the parameters of both the physical and virtual Twins in their environments
    - **Physical to Virtual Connection (bi-directional):** The communications and data connections or processes used to establish this synchronization of the state at the prescribed twinning rate
    - **Physical Processes:** The processes in the real-world environment that will change or impact the state of the physical twin
    - **Virtual Processes:** The processes in the virtual environment (such as analytics or physics-based calculations) that will change or impact the state of the virtual twin
  + **Models and Data**
    - **Temporal or time series data:** IoT data
    - **Master Data:** ERP, EAM systems

# **Learning from research papers**

* **Research paper: Designing Digital Twins for Enhanced Reusability** [https://doi.org/10.1145/3639478.3643102]
  + To enhance reusability in the design
    - Microservice based design.
    - Non-relational graph db with data lake
    - K8s or Containerization
  + Challenges in reusability
    - Poor practices in requirements engineering.
    - User specific requirement / lack of common standards
    - Model-Based Systems Engineering (MBSE) standards for complex systems.
  + Tools and practices that can be considered.
    - Blockchain (?) for data sharing or smart contracts?
    - DevOps, MLOps, AIOps
* **Research paper: A knowledge graph-based construction method for Digital Twin Network** [DOI: 10.1109/DTPI52967.2021.9540177]
  + Novel network paradigm, called digital twin network (DTN) architecture for the future network, which consists of Physical Network, Data Lake, Digital Twin Layer and Network Application Layer.
  + Not directly related it’s about DT of network.
* **Architecting Internet-of-Things-Enabled Digital Twins: An Evaluation Framework** [DOI: 10.1109/WF-IoT62078.2024.10811154]
  + Key capabilities of DT
    - Real Time sync, syncing IOT data.
    - Controlling hardware directly from DT.
    - Accuracy and stability
    - AI Capability
    - Energy & environmental impact
    - Integrating with industry standard systems like
      * Construction industry: Building Information Modeling (BIM) systems. Refer: <https://doi.org/10.1016/j.jobe.2024.108901>.
  + Two common types of architectures for DT
    - tandem system structure
      * doi: <https://doi.org/10.1016/j.jii.2023.100462>
      * doi: <https://doi.org/10.1016/j.autcon.2023.105188>
    - data parallelism in storage and application
      * doi: <https://doi.org/10.1016/j.compag.2023.108243>
      * doi: https://doi.org/10.1016/j.jobe.2024.108901
    - To access both architecture (IOT)
      * doi: <https://doi.org/10.3390/s22114159>
      * NELoRa: Towards Ultra-low SNR LoRa Communication with Neural-enhanced Demodulation
      * doi: <https://doi.org/10.1016/j.iot.2023.101053>
      * doi: <https://doi.org/10.1016/j.apenergy.2018.12.042>
    - To predict CO2 or/and predictive monitoring (AI)
      * doi: <https://doi.org/10.1016/j.enbuild.2023.112851>

# **End of Requirement Specification Document**