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Assumptions for the Application of Internet of Things Solutions in a Smart Factory Demonstrator

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Abstract

The article presents the role and applications of the Internet of Things (IoT) within the concept of a smart factory, with particular emphasis on the Smart Factory laboratory demonstrator at Poznan University of Technology. Key IoT functions are discussed, including the integration of sensors, information systems, and actuators in order to fully digitise production processes. The demonstrator enables replication of real industrial processes, such as production flow control, material inventory supervision, and monitoring of technical equipment operations. The article presents the architecture of the IoT infrastructure, the use of RFID technology, and the implementation of predictive maintenance based on sensor data analysis. The results indicate that IoT implementation significantly increases operational efficiency, improves production quality, and reduces downtimes, although it requires overcoming organisational and technological barriers. The Smart Factory demonstrator serves as a practical platform for research and education in the area of Industry 4.0.

Keywords: Internet of Things (IoT); Smart Factory; Industry 4.0; production systems; RFID; predictive maintenance; 4Factory; production digitalisation

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1. Introduction

New research areas include IoT integration with Digital Twin [1,2], artificial intelligence [3,4], and sustainable production [5,6]. Žarko et al. [1] described a digital twin integrated with the IoT, enabling production simulations. Liu et al. [2] confirm the growing importance of Digital Twin in the automotive industry. The Smart Factory has become a central paradigm of Industry 4.0, with the aim of achieving end-to-end digital integration of industrial processes through the combination of the Internet of Things (IoT), cyber-physical systems (CPS), data analytics and advanced automation [7,8,4]. The concept has been widely discussed in both academic and industrial literature [9,10]; however, current research reveals a significant imbalance between conceptual frameworks and experimentally validated implementations [5,11]. Many contributions remain at an architectural or descriptive level, with limited empirical grounding in reproducible production environments [12].

The Internet of Things is widely recognised as the technological backbone of smart manufacturing [7,9]. Most studies describe layered IoT architectures consisting of sensing, communication, and data processing layers, often supported by cloud or edge computing infrastructures [8,12]. These architectures enable real-time data acquisition and decentralised decision-making [13,10]. Nevertheless, their validation is often limited to simulations or isolated industrial case studies [14], restricting reproducibility and controlled experimentation [11].

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RFID technology has been extensively investigated as a key enabler for product identification, work-in-progress tracking, and production transparency [15,6]. Previous research confirms its usefulness for routing, scheduling, and inventory monitoring [16,17,18]. However, many reported implementations focus on single use cases and lack integration with higher-level production management systems such as Manufacturing Execution Systems (MES) [19], which significantly limits their applicability as experimental platforms for broader production system research.

Condition monitoring and predictive maintenance constitute another major research stream within smart manufacturing and Industrial IoT [20,4]. Numerous publications demonstrate the effectiveness of sensor-based diagnostics and data-driven failure prediction to reduce downtime and maintenance costs [21,22]. However, most of these studies rely on historical datasets or laboratory setups limited to individual machines, rather than integrated multi-station production systems operating under realistic production conditions [5,23].

Recent research trends extend the Smart Factory concept to digital twin technologies, human–system interaction, and data-driven production management [24,1,3]. Digital Twins, in particular, are increasingly recognised as a key enabler for simulation, optimisation, and decision support in manufacturing systems [1,2]. Despite their conceptual maturity, the experimental validation of these approaches is often hindered by the lack of flexible, modular, and fully instrumented laboratory infrastructures that allow systematic and repeatable research across multiple domains of industrial digital transformation [11,24].

The reviewed literature reveals a clear research gap between the theoretical concepts of Industry 4.0 and their experimental verification. Although numerous studies propose architectures, algorithms, and optimisation methods for smart manufacturing systems [7,4,9], there is a notable lack of accessible laboratory-scale Smart Factory infrastructures that support reproducible and methodologically rigorous research [5,11].

In particular, existing work rarely provides:
(i) integrated demonstrators combining IoT sensing, RFID-based tracking, MES-level control, and physical production processes within a single experimental environment [19,5]
(ii) infrastructures enabling controlled experimentation in areas such as production flow control, inventory management, and predictive maintenance under varying operational conditions [20,16,22];
(iii) transparent and sufficiently detailed system descriptions that allow replication, benchmarking, and comparative studies [11,24].

This article addresses these gaps by presenting a Smart Factory laboratory demonstrator explicitly designed as a research infrastructure. The contribution of this work does not lie in the validation of universal performance improvements but in the provision of a modular, instrumented, and extensible experimental platform that enables future quantitative studies on the digital transformation of industrial processes.

The Smart Factory demonstrator provides a fully integrated and physically implemented Industry 4.0 production environment that enables methodologically rigorous and reproducible experimentation beyond the predominantly conceptual or simulation-based approaches reported in the literature.

- It combines material flow, industrial automation (PLC, AS-Interface, ProfiNet), and MES-level production control (4Factory) within a single coherent cyber-physical system.
- Implements product-centred control based on palletised RFID-enabled identification, allowing dynamic routing and operation selection during real assembly processes.
- It enables systematic investigation of mass customisation through configurable products manufactured under one-piece-flow conditions.
- Supports controlled MES-to-shop-floor experimentation in production scheduling, order execution, and material flow coordination under realistic operating conditions.
- It provides a modular, multi-station laboratory infrastructure suitable for analysing system-level phenomena such as bottlenecks, disturbances, and flow dynamics.

The laboratory further offers substantial potential for extended research on digitalised manufacturing systems, which is elaborated on and experimentally exploited in the following sections of the article.

2. Laboratory Production System Demonstrator – Smart Factory

The production system in the Smart Factory laboratory at the Poznan University of Technology is being built to support research and teaching on various technical and organisational solutions compliant with the smart factory concept. The equipment enables the replication of major processes that occur in real production systems. The production process involves the assembly of products from parts in the form of LEGO bricks. These were adopted as the basic building elements of the final products, ensuring complete flexibility in product configuration according to the idea of customisation—one of the foundations of Industry 4.0. Product flow on the line follows the one- -piece-flow principle, using transport pallets as carriers. It is built from modules that enable production scheduling, material flow monitoring, and assembly line control.The Smart Factory laboratory production system demonstrator, developed at Poznan University of Technology, constitutes an integrated research and teaching platform dedicated to the analysis and validation of manufacturing concepts compliant with the Industry 4.0 paradigm. The system has been designed as a physical representation of a digital factory in which the automation layer, the industrial communication infrastructure, and the production management IT systems are tightly integrated. Its structure enables replication of key processes that occur in real manufacturing environments, in particular with regard to material flow, order execution, and adaptation to dynamically changing customer requirements.

The core of the demonstrator is a modular automated assembly line composed of three transport loops with workstations distributed along their paths. This architecture allows for flexible configuration of product routing and reconfiguration of the process structure depending on the experimental or educational scenario. The transport of workpieces is realised by means of pallets, which ensures unambiguous identification of individual production units and enables the implementation of the one-piece-flow principle, characteristic of modern high-flexibility manufacturing systems with short lead times.

LEGO bricks are used as the physical representation of products, enabling the modelling of a wide range of product variants while maintaining a common component base. This approach makes it possible to experimentally implement the concept of mass customisation, in which each product may have an individual configuration while preserving the continuity and automation of the assembly process. The product configuration data are integrated with the line control system, allowing dynamic adjustment of the operation sequences to the requirements of each specific order.

The automation layer of the demonstrator is based on a PLC-controlled system integrated with power supply units, safety modules, and industrial I/O components, ensuring both functional reliability and compliance with industrial safety standards. Communication between devices is implemented using AS-Interface and ProfiNet industrial networks, reflecting the hierarchical architecture typical of contemporary manufacturing systems, in which field-level devices, control systems, and higher-level IT systems are seamlessly interconnected.

Supervisory production management is performed by the 4Factory IT system, which acts as a local Manufacturing Execution System (MES). It is responsible for production scheduling, coordination of manufacturing orders, material flow monitoring, and real-time supervision of the assembly process. The integration of 4Factory with the automation layer provides a coherent implementation of the digital factory concept, in which decisions taken at the information system level are directly translated into actions in the physical production system.

The described demonstrator constitutes a coherent cyber-physical research environment that enables the analysis and validation of solutions related to flexible manufacturing systems, IT–OT integration, and production organisation under conditions of high product variety. Detailed descriptions of individual system components and their application in the conducted research are provided in the following chapters.

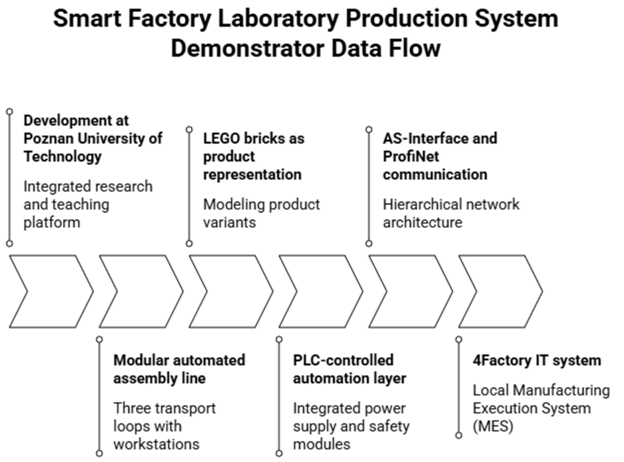

Figure 1. Smart Factory Laboratory Data Flow

3. Smart Factory Use of IoT to Control the Production System

3.1. IoT Infrastructure Model

Within the presented production system demonstrator, a digitalisation infrastructure was developed (Fig. 1). The equipment enables the supervision of production system areas based on IoT solutions.

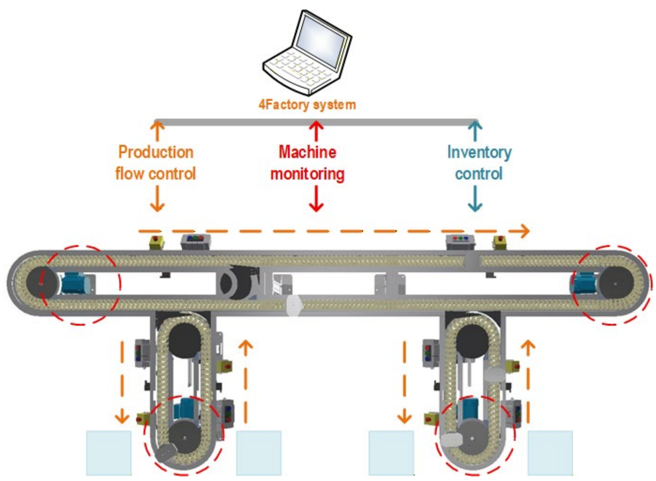

Figure 2. IoT Infrastructure Model

Based on data collected from the production process, the 4Factory system enables real-time control and monitoring of material flow, inventory levels at production workstations and transport line parameters.

Research on the Production Line Evaluate the efficiency, flexibility, and adaptability of the assembly line in laboratory conditions and analyse possibilities for implementing Industry 4.0 solutions.

Proposed Experiments and Research Tasks:

1. Testing different line and transport loop configurations:
- Compare throughput for different workstation sequences.
- Study the impact of assembly cycle durations on production efficiency.

2. Analysis of production scheduling impact:
- Simulation of varying workstation loads.
- Evaluation of efficiency under dynamic changes in order priorities.

3. Testing product customisation:
- Study the impact of changes in product configuration on the time it takes to complete the order.
- Analyse the limitations in adapting the process to different product variants.

Analysis Methods:
- Measure Overall Equipment Effectiveness (OEE).
- Analyse material flow and cycle times.
- Compare experimental results with simulation models.

3.2. Production Flow Control

The foundation for initiating the production process is the schedule developed in the 4Factory system. It contains detailed information on the sequence of manufacturing individual products and the sequence of production operations performed on specific workstations. Based on this schedule, the system determines the optimal route for product flow, taking into account the availability of the workstation, the required cycle times, and production priorities. The completed schedule is then automatically transmitted to the PLC controller, which is responsible for the physical control of the transport pallets that carry the products.

The pallets are equipped with RFID transponders, which constitute a key element of the identification and production-tracking system. Reading RFID tags by the heads installed at various stages of the line enables unambiguous identification of the pallet and the production order assigned to it. As a result, each pallet can be automatically directed to the correct workstation according to the schedule. Upon arrival at a production operation, the tag readout triggers the display of information on the operator panel. The operator receives detailed instructions related to the task, such as process parameters, visual documentation, and specific quality requirements. Upon completion of the operation, the operator releases the pallet, which is then automatically directed to the next scheduled stage.

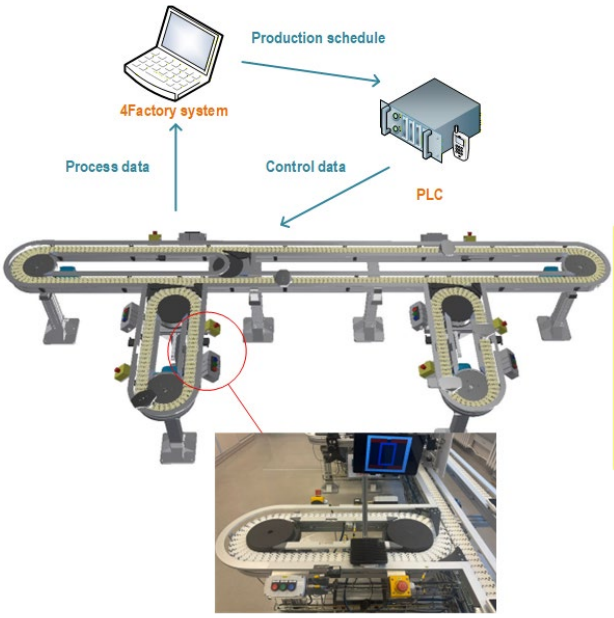

Figure 3. Information flows in the Smart Factory line

The use of RFID technology enables not only the automation of production flow, but also the continuous collection of real-time data on the current status of operations, production orders, and load of the workstation. This information is continuously transmitted to the 4Factory system, enabling immediate monitoring of schedule execution, identification of potential deviations, and analysis of production performance indicators (including OEE, changeover times, and downtime). This allows for rapid response to process issues and increases the transparency and flexibility of the entire workflow.

Operators can also report events that occur during the execution of production orders via operator panels when such events prevent operations from being completed according to established standards. These events may include machine failures, material shortages, as well as quality or organisational issues. All reported information is recorded in the 4Factory system and is linked to specific orders and operations, allowing subsequent analysis of the causes of deviations, identification of bottlenecks, and implementation of improvements to the production process. Thus, the system serves not only as a production-flow control tool, but also as a support in monitoring, reporting, and continuous improvement.

Research on IoT and Production Flow Control
Assess the capabilities of IoT for production automation, product flow monitoring, and integration with control systems.
Proposed Experiments and Research Tasks:

1. Integration of sensors and RFID:
- Test the accuracy of the pallet and order identification.
- Study the impact of RFID read delays on production control.

2. Automatic Product Flow Control Testing:
- Analyse the efficiency of pallet routing in various production scenarios.
- Study the impact of workstation failures on automatic rerouting.

3. Real-time data analysis:
- Monitor performance indicators (OEE, changeover times, downtime).
- Test the system's ability to detect schedule deviations and respond automatically

Analysis Methods:
- Data logging in the 4Factory system and statistical analysis.
- Simulation of failure scenarios and system resilience tests.
- Comparison of manual vs. automated flow control under laboratory conditions.

3.3. Monitoring of Material Inventory

Production workstations are equipped with flow racks in which containers with parts and assemblies used in the product assembly process are stored. The racks are divided into zones and locations designated for full and empty containers, which improves workplace organisation and minimises the risk of errors. The replenishment of material on the racks is based on the kanban method, which ensures smooth and continuous delivery of components according to the actual demand. Each storage location is equipped with an RFID reader that enables automatic identification of containers and their contents. The information stored on the RFID tags constitutes a digital description of the container, and the operation of the readers is controlled by the PLC controller. Communication with the 4Factory system is carried out wirelessly via an industrial WiFi access point, eliminating the need for cabling and increasing the flexibility of workstation configuration.

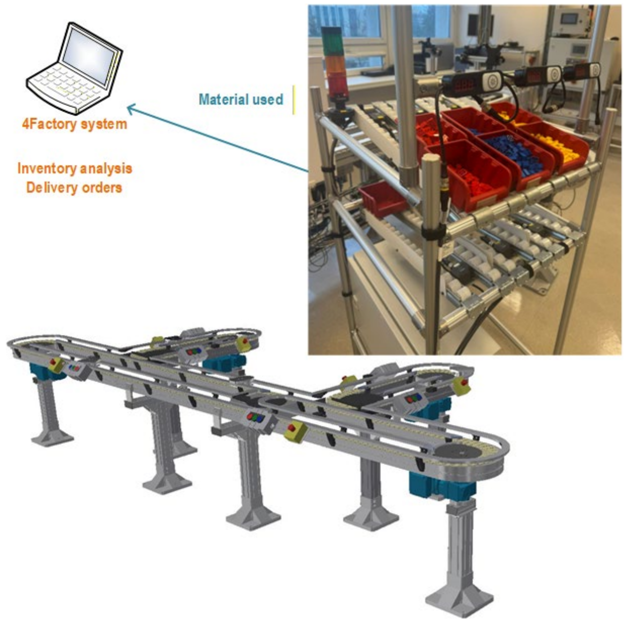

Figure 4. Material flow supervision

As parts are consumed during the execution of assembly orders, the operator places an empty container in the designated location. Once placed, the RFID reader performs a readout, which automatically updates stock levels in the 4Factory system. When the minimum stock level is reached, the system generates a replenishment request for the corresponding workstation rack. This ensures continuity of component supply and significantly reduces the risk of production stoppages due to material shortages.

Inventory supervision is carried out by the warehouse module of the 4Factory system. For each rack, storage locations are defined along with associated part types, as well as minimum and maximum stock levels. The containers stored on the racks have predefined standard quantities of parts, enabling for precise planning of material requirements.

Research on Material Inventory Monitoring:
Evaluate the effectiveness of digital material management using RFID, Kanban, and automated replenishment.

Proposed Experiments and Research Tasks:

1. Automatic container identification testing:
- Assess the correctness of RFID reads under various operating conditions.
- Analyse identification errors and their impact on production.

2. Research on optimising material replenishment:
- Test different minimum stock levels and replenishment frequencies.
- Analyse the system response to supply interruptions.

3. Material flow efficiency analysis:
- Compare response times to material shortages in manual vs. automated scenarios.
- Study the integration of inventory data with production schedules.

Analysis Methods:
- Event log and time-based analysis in the 4Factory system.
- Simulation of shortage and overstock scenarios.
- Error analysis and correlation with line performance.

3.4. Monitoring the Operation of Technical Equipment

An essential element of the infrastructure is the set of operating and position sensors (inductive or magnetic) used to diagnose moving components of the production line, such as actuators, assembly fixtures, conveyors and drive elements. These sensors serve as the primary source of information about the current state of the equipment — they signal, among other things, the position of actuators, confirm the completion of movements, and report stoppages, overloads, or abnormal operating cycles. Their readings are continuously transmitted to the PLC controller, which analyses them for process correctness and reacts immediately in case deviations are detected.

Such measurements enable continuous real-time diagnostics of the equipment. The system is capable of capturing early symptoms of failures, such as actuator slowdown, failure to reach an end position, or increased frequency of micro-stoppages. This information can be used to automatically adjust equipment operating parameters, for example, by regulating speed, modifying control logic, or switching operating modes depending on the current condition of the devices.

In combination with the IoT platform, all sensor data are aggregated, recorded, and analysed over the long term. This enables the implementation of predictive maintenance strategies that involve forecasting potential failures based on trends and patterns observed in the behaviour of the equipment. The platform can detect anomalies, create component degradation models, and estimate the most probable time of failure occurrence. With this approach, maintenance and component replacement can be carried out precisely when needed — before they cause process downtime.

Implementing predictive diagnostics not only eliminates unplanned interruptions, but also increases the durability and reliability of equipment, enables better planning of maintenance activities, and reduces costs associated with plant maintenance. As a result, the entire production system becomes more stable, resistant to failures, and optimised for continuous operation.

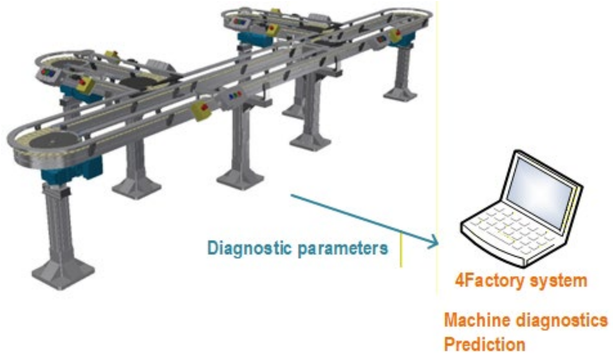

Figure 5. Monitoring the operation of technical equipment

Research on Equipment Operation Monitoring and Predictive Diagnostics
Assess the operation of sensors and predictive diagnostic strategies to increase assembly line reliability.
Proposed Experiments and Research Tasks:

1. Testing position and operation sensors:
- Verify the accuracy of position, speed, and fault signals.
- Analyse the impact of measurement errors on line control.

2. Research on predictive diagnostics:
- Identify early signs of failures (slowdowns, micro-stops, incorrect positions).
- Test predictive failure algorithms and evaluate the accuracy of the forecast.

3. Maintenance optimisation:
- Maintenance of the plan based on the IoT data and predictions.
- Analyse the effect of predictive diagnostics on downtime and maintenance costs.

Analysis Methods:
- Trend and deviation analysis of sensor signals.
- Compare predicted failures with actual events.
- Test intervention scenarios based on the prediction results.

4. Conclusions

The solutions presented in this article confirm that the Internet of Things (IoT) is a key element of the smart factory concept and forms the foundation for the transformation of industry toward Industry 4.0. Integration of sensors, information systems, and actuating devices enables complete digitalisation of the production environment and provides real-time access to data, allowing rapid and accurate operational decision-making.

The application of IoT technologies in the SmartFactory laboratory demonstrator at Poznań University of Technology demonstrates that even under educational and research conditions, it is possible to replicate key processes of real production: control of product flow, monitoring of material inventories, and supervision of technical equipment operation. Integration of RFID, position sensors, operator panels, and the 4Factory system enables process automation and ensures complete transparency of information throughout the production cycle.

The results of the solutions presented indicate that IoT technologies can significantly improve operational efficiency by eliminating human errors, reducing response times, minimising unplanned downtime, and improving production planning and execution. In particular, the importance of sensor data analysis and predictive diagnostics should be emphasized, as they enable early fault detection and minimize maintenance costs.

At the same time, the implementation of IoT involves overcoming technological and organisational barriers, such as system interoperability, data security issues, and the need to develop digital competencies of employees. Experience in building the demonstrator confirms that the key to success lies in a coherent digitalisation strategy and the gradual integration of successive system modules.

In summary, IoT is becoming a central element of modern production systems, enabling the creation of highly efficient, autonomous, and flexible smart factories. The Smart Factory demonstrator serves as an example of the practical application of this technology and can function both as a research platform and as an educational tool, preparing future engineers for work in real Industry 4.0 environments

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