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Comparative Analysis of a Traditional and an Industry 4.0-Based Manufacturing Cell through the Example of a Cylindrical Gear

Bráda Csaba
Óbuda U. Alba Regia Faculty,
Székesfehérvár 8000, Hungary
Email: brada.csaba@uni-obuda.hu

Pethő Levente
Óbuda U. Alba Regia Faculty,
Székesfehérvár 8000, Hungary
Email: leventepetho3@gmail.com

Abstract — ***This paper compares a traditional production line and an Industry 4.0oriented manufacturing cell through the example of a cylindrical gear produced in three aluminium variants. The study evaluates productivity, flexibility, quality, and cost efficiency, and examines the impact of Industry 4.0 elements such as sensors, data analytics, and automated control. Results show that traditional systems remain effective in small- and mediumscale production, while Industry 4.0 solutions excel in high-volume and precision-demanding environments. The findings highlight the potential of hybrid strategies that combine conventional robustness with digital adaptability.***

Keywords: Industry 4.0, manufacturing cell, gear, comparison, comparative analysis.

I. INTRODUCTION

The primary aim of this publication is to provide a comparative analysis of traditional manufacturing systems and those that comply with Industry 4.0 standards. The study focuses on comparing the operating principles, tools, and organizational logic of two fundamentally different approaches to manufacturing. The subsequent analysis also considers various application contexts, advantages, and challenges.

It is important to emphasize that this paper does not aim to rank the two approaches or to declare one superior. Rather, the objective is to identify the manufacturing environments and conditions where either system can offer greater benefits.

The purpose of this work is to highlight, from a practical perspective, the factors that influence the advantages of a given system, as well as the compromises and challenges that must be addressed when selecting a manufacturing strategy. In this way, the paper seeks to provide support for students and educators involved in the development, design, or optimization of manufacturing systems.

In this study, the term “traditional manufacturing system” refers to production structures that rely little or not at all on digital technologies. In such systems, the level of automation is generally lower, human labour plays a more dominant role, and decision-making is conducted by people based on experience. Examples include classical production lines, manual or semiautomated workflows, and manufacturing cells operating with quite simple control systems.

By contrast, Industry 4.0-based systems represent integrated, digitized, and often selforganizing production environments. In such manufacturing cells or lines, the various devices communicate with each other, collect and process data about themselves and their surroundings, and can make decisions based on predefined algorithms. The aim of these systems is to minimize the need for human intervention, thereby reducing errors and optimizing manufacturing efficiency.

As part of this paper, specific examples designed by the author are presented to demonstrate the characteristics of these systems and ways in which they can be optimized. Special attention is given to the forms of human–machine collaboration and the role of data-driven decision-making.

II. INDUSTRY 4.0 CONCEPT AND FOUNDATIONS

Industry 4.0 involves linking physical and digital systems so that production lines, machines, sensors, and IT systems become intelligent, networked units. These systems not only collect data but are also capable of real-time analysis and automatic optimization of production processes. Industry 4.0 fundamentally relies on technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, cloud systems, robotics, cyber-physical systems (CPS), and big data analytics.

In an Industry 4.0-compatible manufacturing system, machines can communicate with each other, make decisions, and adapt to changing conditions.

The close integration between systems makes production more flexible, faster, and cost-effective, depending on the characteristics of the manufactured product. This is particularly important in today's rapidly changing market environment, where personalized, small-batch production is increasingly common.

The aim of Industry 4.0 is not merely to automate production but to create an intelligent, adaptive, and predictive system capable of independently responding to unexpected events, errors, or order changes. This significantly reduces the need for human intervention while increasing manufacturing efficiency and quality.

It is important to note, however, that Industry 4.0 is not just a technological innovation but also a shift in mindset. It represents a complex ecosystem in which not only production but also logistics, maintenance, quality assurance, and product design are conducted in a digital, data-driven manner. This requires not only innovative technologies but also new competencies, training, and corporate culture.

The introduction of Industry 4.0 is therefore not a universal recipe but a process that varies by company. Its success depends heavily on existing infrastructure, human resources, financial capacity, and the strategic commitment of management.

III. MACHINE AND HUMAN INTERACTION IN MANUFACTURING

The goal of industrial automation is to make production processes faster, more predictable, and cost-effective. Automation replaces human tasks that are typically repetitive, well-defined, and do not require creative or intuitive decision-making.

What makes a task automatable?

Several factors determine whether a task can be automated. A basic requirement is that the task must be precisely defined: it should consist of clear steps with measurable inputs and expected outputs. For example, screwing a bolt, positioning a component, or performing a simple quality check can be relatively easy to automate. It is also important that the environment is stable and well-controlled—for example, closed manufacturing cells have fewer external disturbances, making it easier to design an automated system.

Where do automated lines excel?

Automated production lines perform exceptionally well in areas where the goal is to produce large quantities of standardized products. Their advantages include high speed, excellent repeatability, favorable error rates, and reduced physical strain on workers. Modern systems can already perform self-diagnostics, predictive maintenance, and dynamic adjustment of production parameters.

What cannot be replaced by machines?

Machines are excellent for rule-based tasks but still face challenges in replacing complex human skills such as complex decision-making, flexibility, emotional intelligence, or creativity. Problemsolving, handling unexpected disruptions, or rapidly adapting to new processes are areas where humans still outperform machines. Furthermore, machines cannot weigh moral, ethical, or social considerations, which may be essential in certain situations.

What is the human role in an automated environment?

In a modern, Industry 4.0-compatible manufacturing environment, the human role is transformed but not eliminated. Instead of physical labor, supervision, control, data interpretation, decision-making, and development take center stage. Tasks include system maintenance, optimization, and identifying the causes of production anomalies. Operators must acquire additional skills and training to transition from traditional machine operation to these new responsibilities. A general shift in mindset is also required to embrace the interpretation and use of production-related data.

IV. WORKPIECE AND MANUFACTURING

The comparative analysis of this thesis is realized through examining a traditional and an Industry 4.0-compliant manufacturing cell. The chosen workpiece is a gear, a common machine element used in many assemblies. Its manufacturing operations include turning, gear cutting (e.g., hobbing or milling), drilling, and final quality control.

The study covers the production of six different types of gears differing in the outer diameter (40mm, 60mm, 80mm) and the number of teeth (20,30,40).

The ability to handle these three types ensures that the flexibility, changeover capability, and production strategy of the production lines can be compared. This makes it possible to analyze the steps required to manufacture each type in the two different systems and to examine differences in efficiency, manageability, data handling, and labor requirements.

The aim of the manufacturing system is not merely to produce parts but to highlight when a traditional approach is more advantageous and when it is worth exploiting the possibilities of Industry 4.0.

The study does not aim to identify a “better” or “worse” system but to determine which approach offers more benefits in different manufacturing situations.

V. TRADITIONAL MANUFACTURING PROCESS

The traditional manufacturing cell is built on linear, sequential operations performed on separate machines or workstations. The operator moves the workpiece from one machine to another, starting each operation with manual setup and supervision.

During the process, there is little or no data communication between machines. Production status is typically tracked in a simplified manner using spreadsheets or verbal reports. After production, the number of good parts, scrap, and rework quantities are recorded in a digital system.

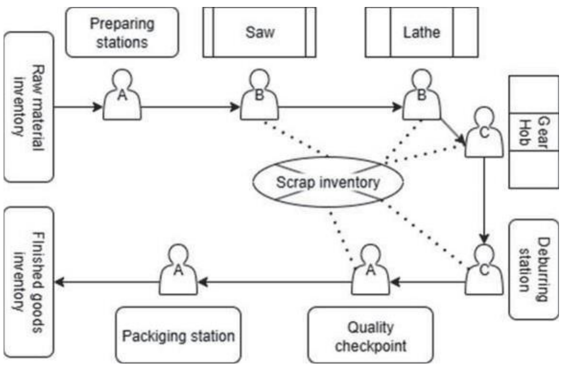
Process main steps:

1. Raw material preparation: bar stock cutting with manual or semi-automatic saw.
2. Turning of outer diameter and creation of internal bore.
3. Gear cutting using a gear milling cutter.
4. Manual removal of burrs.
5. Quality inspection using calipers, micrometers, or gauges.
6. Manual movement of the part between processes.

Several layout alternatives illustrate the flexibility of traditional manufacturing. The arrangement has a direct impact on efficiency, cycle time, and work organization.

VI. TRADITIONAL MANUFACTURING BLOCK DIAGRAM

The block diagram of the traditional manufacturing cell follows a simple, linear layout in which the individual workstations are arranged sequentially.



6.1 Figure: Traditional Manufacturing

The primary goals of this design are to maintain the correct order of operations, ensure easy movement for operators, and keep the production process transparent. Material flows from left to right.

By design, 2–3 operators are present in the cell, and their assignments can be freely adjusted according to their experience.

The operators' tasks in this structure include:

- Workpiece preparation.
- Manual control and supervision of machining equipment.
- Quality inspection.
- Maintenance activities.
- Manual documentation of production data.
- Communication with other operators.

VII. INDUSTRY 4.0 MANUFACTURING PROCESS

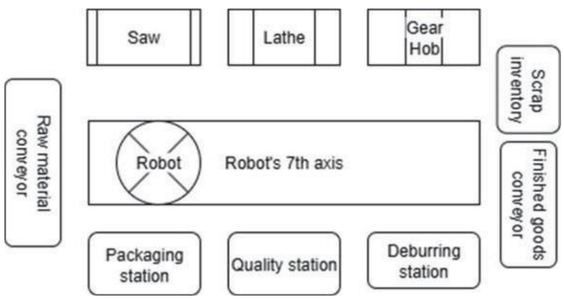
The design of the Industry 4.0-compliant manufacturing cell is based on the latest technologies to achieve efficient, flexible, and fully automated production.

Key features:

- Digital production order reception (from MES or ERP)
- Workpiece identification and preparation using RFID.
- Automated gripping and feeding (robot arm with 7th axis)
- CNC machining with real-time sensor data
- Camera-based automatic quality control
- Data collection and cloud-based feedback (IoT)
- Automated storage and reporting to the central system

The main stages include order processing, sawing, turning, milling, deburring, quality control, and packaging, with robotic transport of raw materials, workpieces, and finished products.

VIII. INDUSTRY 4.0 BLOCK DIAGRAM



7.1 Figure: Industry 4.0 block diagram

The system's key advantage is modularity and intelligent control: the cell can adapt to changing production needs without lengthy downtime or manual intervention. Continuous data collection enables predictive maintenance and production optimization.

- The main elements of the cell include:

- Raw material conveyor
- Automatic saw - Lathe
- Gear milling machine.
- Deburring station
- Camera-based quality inspection station
- Packaging station - Finished product conveyor. - Scrap collector
- Industrial robot arm and 7th axis

The operator's role is almost completely transformed compared to traditional manufacturing, focusing on system monitoring, data management, program handling, anomaly intervention, and maintenance.

IX. INDUSTRY 4.0 COMMUNICATION ARCHITECTURE

The Industry 4.0 manufacturing cell features real-time communication between machines, systems, and humans. Every component must communicate with each other and a central system to enable accurate process tracking.

Communication includes:

- Database interactions for fault logging, tolerance monitoring, and product tracking via RFID.
- Robot coordination with conveyors, machining stations, quality control, packaging, and scrap collection.
- PLC-based real-time data flow to ensure smooth operation.

The operator now performs data verification, troubleshooting, and system supervision rather than solely physical control.

Communication Parties:

Database:

Failures are recorded in the database. If a disturbance occurs at one station, it must be communicated to the others in order to suspend production. If the system produces values beyond tolerance, it must send feedback to the operator.

The RFID of every manufactured product and its associated data must be logged. This includes whether the final product is suitable for the customer, requires rework, or is scrap.

Raw Material Conveyor:

Database – Based on extracted data, it initiates the transport of raw materials and stops the process when the material reaches the end-position sensor.

Robot – The robot must be aware that the raw material has reached the predefined position.

Processing Stations:

Database – The database must contain at least an approximate status of the tool. It must log when and what type of material entered and exited the workstation so that its status can be tracked and modified if necessary.

Robot – The robot must know the current work stage of the station and whether it is accessible and loadable.

Quality Control Station:

Database – The station must transmit cameracaptured images to the database. In case of discrepancies, this plays a particularly important role.

Robot – The robot must know the current work stage of the station and whether it is accessible and loadable.

Packaging Station:

Database – The station must provide information to the database about the accurately packaged good product.

Robot – The robot must know the current work stage of the station and whether it is accessible and loadable.

Scrap Collector:

Robot – Database communication. Based on how many times the robot moved to the scrap collector, the amount of scrap produced can be determined. Therefore, the scrap collector does not need to be equipped with additional sensors.

Robot's 7th Axis:

Robot – Continuous communication must be maintained between the robot and the axis to ensure that work processes can be carried out.

Most of the required data flow can be easily implemented using PLCs. It is essential that communication is real-time. The operator's role has significantly changed compared to traditional control: they not only perform physical interventions but also carry out data verification, troubleshooting, and system monitoring.

This network enables data-driven decisionmaking, instant fault detection, and real-time optimization of the production process—capabilities that were difficult or impossible to achieve with traditional production lines.

X. COMPARISON OF PROCESSES

The aim of this chapter is to provide an extended comparative evaluation between the traditional manufacturing process model and Industry 4.0-based systems.

The essence of the traditional model lies in its linear and segmented progression, where decisionmaking and quality control are primarily in the hands of human operators. In this setup, intermediate inspections occur at various stages of the workflow—for example, after cutting, turning, or gear machining, product parameters are manually checked or assessed at inspection points, and decisions are made regarding rework or scrapping. The advantage of this experience-based model is that skilled operators can perform quick, situationspecific interventions in particularly complex scenarios. However, this approach carries a higher risk of errors, as manual inspections are often delayed, may result in inconsistent quality levels, and coordination between workflow stages can become cumbersome due to the lack of continuous feedback.

In contrast, the Industry 4.0-based structure is equipped with digital and automated solutions, enabling the manufacturing process to operate not only in predefined steps but also dynamically, based on real-time data flow and processing. The application of cutting-edge technologies allows deviations in raw material and inventory management, as well as in machine operations, to be identified early in the production phase. This enables predictive maintenance and intelligent decisionmaking. Real-time quality control and data continuously monitored by algorithms significantly reduce production errors and correction times, although the system requires high-level technological investment and a different type of operator expertise.

From the outlined perspectives, the comparison essentially reflects a clash of two philosophies: while the traditional model relies on human factors and experience-based, segmented feedback, the Industry 4.0 approach aims to eliminate delays and error potential stemming from human nature through continuous data flow, predictive analytics, and automated interventions. This can lead to increased productivity, improved quality assurance, reduced cycle times, and significant long-term cost savings. However, the traditional system may prove more flexible in cases where environmental or productspecific characteristics prevent standard automation algorithms from making optimal decisions, making human intervention indispensable.

Furthermore, the Industry 4.0 model enables integrated process management, where every phase of the production cycle—from raw material intake to final product packaging—operates within a centralized, interconnected system. An example of such a process system was detailed in previous chapters of this thesis. This system-level integration not only improves production speed and quality but also supports early forecasting of maintenance and optimization decisions, which can lead to a reduction in the proportion of defective workpieces. In contrast, the traditional model is decentralized, with less transparent data flow between subsystems, making rapid error detection and correction more difficult.

The comparative evaluation highlights that Industry 4.0 systems, driven by digital integration, are more competitive, flexible, and capable of significantly reducing unforeseen disruptions in the long run. However, the high investment costs and comprehensive challenges associated with these systems must not be overlooked. The experiencebased flexibility and adaptive human decisionmaking of the traditional model remain valuable in situations where unique production requirements demand personal intervention. In future industrial systems, it is likely that both approaches will be applied in parallel: automated, real-time data-driven decision support will be complemented by the role of experienced operators, who will ensure continuous product compliance by reviewing system-generated alerts and recommendations.

XI. SUMMARY

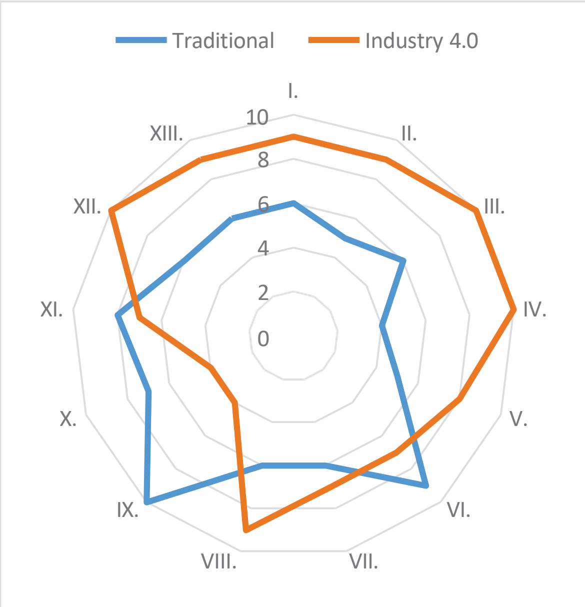
The aim of this research was to compare the operation, structure, advantages, and limitations of traditional and Industry 4.0-oriented manufacturing cells through the example of a specific workpiece. The investigation revealed that both manufacturing approaches possess strengths that may make one more advantageous than the other depending on the context.

Traditional systems, due to their simplicity and proven reliability, remain suitable for lowcomplexity, small- or medium-batch production. In contrast, Industry 4.0 technologies—including automation, sensor networks, robotics, and datadriven decision-making—are particularly beneficial in high-volume production environments with stringent quality requirements or frequent changeovers.

A key finding is that Industry 4.0 is not solely about technology—it also represents a shift in mindset. Human labour does not disappear but transforms: physical tasks give way to supervisory, system-level, and decision-making roles. This demands new skills and ways of thinking from industrial workers.

The future of manufacturing lies in integrating both approaches—where the stability of traditional systems complements the flexibility of Industry 4.0. Continuous development and research are essential for industrial stakeholders to fully leverage the opportunities offered by digitalization.

To illustrate the differences between the traditional and Industry 4.0 based manufacturing cells this evaluation table was created based on my own observations and experiences. The table compares the two systems across several operational and organizational aspects, assigning numerical values (1-10) to represent their relative performance and capabilities.



XI.I figure: difference evaluation diagram

I.	Process stucture	VIII.	Logistics and inventory support
II.	Decision-making method	IX.	Cybersecurity
III.	Quality control	X.	Investment requirements
IV.	Data collecting and processing	XI.	Operator's role
V.	Maintenance	XII.	Performance monitoring
VI.	Flexibility and intervention	XIII.	Innovation potencial
VII.	Scrap and rework handling		

XI.II figure: table for evaluation diagram content

Based on the research findings, there is potential to develop software capable of evaluating whether a given process can be technically and economically automated based on predefined parameters. Such a system could consider production volumes, product variability, investment costs for automation, the condition of existing machinery, and human resource requirements.

The examples examined in the thesis (e.g., production of cylindrical aluminum gears) demonstrate that even seemingly simple products may require diverse technological and organizational approaches. The choice is often not straightforward and involves trade-offs: for instance, an automated system may be faster and more precise, but its investment cost is high and only pays off at larger batch sizes. Such software could provide answers to these questions through objective, calculation-based decision support.

In the long term, the concept could be enhanced with an AI-based learning module that refines predictions using historical production data. This would allow the system not only to evaluate individual data points but also to improve its recommendations through experience and machine learning.

In conclusion, future manufacturing decisions should not rely solely on technological intuition or experience but increasingly on data-driven, modelbased evaluation systems. Such a decision-support tool could also contribute to the competitiveness of domestic small and medium-sized enterprises by helping them identify and optimize manufacturing development opportunities in a structured way.

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All diagrams included in this thesis were created manually using the draw.io software. All tables presented in the thesis were manually compiled using Microsoft Excel. The preparation of this thesis was supported by Artificial Intelligence tools. Specifically, OpenAI ChatGPT and Microsoft Copilot were used to assist with text editing suggestions, structural ideas, and content formatting.