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Cognitive robotic systems for sustainable development and competitive advantage: Eliminating lean wastes

Mikhail Kinebas[1]*, Serhii Ivanov[2], Mykola Ivanov[3]
[1]Department of Economics, Zaporizhzhia National University, Zaporizhzhia, Ukraine; mikhail.kinebas@gmail.com (M.K.)
[2]Department of Economic Cybernetics, Zaporizhzhia National University, Ukraine.
[3]Department of Economics, Zaporozhye National University, Zaporizhzhia, Ukraine.

Abstract: This study explores how the integration of cognitive robotic systems into lean manufacturing can simultaneously address the elimination of the seven classical wastes and support sustainable development in Ukrainian enterprises. A simulation-based methodology was applied, using a digital twin of a manufacturing system. Three scenarios were compared: (A) baseline operations with traditional lean practices, (B) conventional automation, and (C) integration of cognitive robotics. Key performance indicators (OEE, lead time, FPY, scrap rate, energy consumption, and inventory levels) were used for evaluation. The results show that cognitive robotics reduces order fulfillment time by more than 30%, lowers defect rates by over 70%, and decreases energy consumption per unit of production by about 20%. At the same time, first-pass yield (FPY) and overall equipment effectiveness (OEE) significantly increase. Cognitive robotic systems provide measurable advantages compared to both traditional lean and conventional automation, confirming their role as a driver of sustainable competitiveness. For manufacturing and Ukrainian manufacturing, cognitive robotics can mitigate labor shortages, improve supply chain resilience, and reduce costs while supporting sustainable development goals (SDGs). The Lean 5.0 framework may serve as a strategic basis for post-war industrial recovery and modernization.

Keywords: *Cognitive robotics, Economy, ERP/MES integration, Industry 5.0, Lean manufacturing, Seven wastes, Sustainable manufacturing, Ukrainian manufacturing.*

1. Introduction

Lean Manufacturing has long been considered one of the most effective strategies for increasing productivity and reducing costs. Its key feature is the systematic elimination of seven classic types of waste: overproduction, waiting, transportation, overprocessing, excess inventory, unnecessary movements, and defects [1-3]. Practice shows that the implementation of Lean principles has allowed many enterprises to achieve tangible results in the fields of efficiency and quality.

At the same time, modern challenges such as a shortage of skilled labor, growing demand for individualized products, disruptions in global supply chains, as well as increased attention to energy efficiency and reducing the carbon footprint, call into question the sufficiency of traditional Lean tools to ensure competitiveness in the new conditions.

The transition from Industry 4.0 to Industry 5.0 focuses on new principles of production development, in particular, on human-centricity, cognitive automation, sustainability, and adaptability of systems. In this context, cognitive robotic systems are becoming increasingly important, combining classical robotics with artificial intelligence (AI) [4], digital twins [5] integration with ERP/MES systems and machine vision technologies. Unlike traditional robots, such systems are not limited to executing pre-set programs; they are able to interpret tasks, adapt to changing conditions, and optimize

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* Correspondence: mikhail.kinebas@gmail.com

actions in real time. This opens up new opportunities for eliminating production losses and creates the basis for the transition to the Lean 5.0 concept.

Despite the significant amount of research devoted to both the Lean concept and AI-based automation, there is still a lack of systematic work that directly links the elimination of the seven classic losses with the use of cognitive robotics in the context of sustainable development and maintaining competitive advantages. This deficiency is especially noticeable for Ukrainian industrial enterprises operating under conditions of instability and resource constraints. This article aims to fill a gap in the current literature. To achieve this goal, we formulate the following research questions:

Q1. How can cognitive robotic systems integrated into the Lean 5.0 framework simultaneously contribute to the elimination of the seven classic losses and ensure sustainable development of production?

Q2. How effective is the combination of automatic programming, adaptive perception, integration with ERP/MES systems, and AI-based quality control in reducing production losses compared to traditional automation?

Q3. How can the implementation of cognitive robotics in Ukrainian enterprises enhance their competitiveness in the face of labor shortages and supply chain instability?

Q4. Can cognitive robotic systems create measurable synergies between Lean waste elimination and sustainability indicators (including energy efficiency, carbon footprint reduction, and resource efficiency)?

2. Literature Review

2.1. Lean Manufacturing and the "Seven Wastes" Concept

Lean Manufacturing originates from the Toyota Production System (TPS) [6] the main task of which is to eliminate all types of waste that do not create added value. Traditionally, seven classic wastes are distinguished [7]:

1. Overproduction.
2. Waiting.
3. Transport.
4. Overprocessing.
5. Inventory.
6. Motion.
7. Defects.

These wastes form the basis for optimizing production, and most research in Lean focuses on their elimination. However, recent reviews (2021–2025) indicate that traditional Lean tools are often insufficient for environments with a high level of turbulence, such as unstable supply chains, staff shortages, or high requirements for product customization.

2.2. Lean 4.0: Conversion with Digital Technologies

Industry 4.0 has introduced digital tools into the Lean environment: IoT, Big Data, cyber-physical systems, cloud platforms [8]. This approach is called Lean 4.0, and it allows for increased process transparency, reduced waiting times, and optimized transport flows. Recent studies have shown that Lean 4.0 provides additional benefits but has two significant limitations:

- Automation is mostly “rigid” and requires careful reprogramming,
- Human interaction is limited, which reduces the flexibility of production systems.

2.3. Mapping the “7 Losses” of Lean to Cognitive Modules

The generalization of the results of modern research has allowed the development of a systemic connection between classical Lean losses and cognitive solutions offered within the framework of Lean 5.0. This approach establishes a basis for the quantitative assessment of the impact of cognitive modules on the elimination of losses and provides the possibility of integrating the results into the KPI system of the enterprise.

Each of the "7 losses" is reflected in the corresponding cognitive solutions and sets of performance indicators. This allows for a transparent mapping of "loss → cognitive solution → KPI," which demonstrates how Industry 5.0 technologies provide a direct connection between operational improvements and the strategic goals of sustainable development.

Table 1.
Mapping of Lean wastes to cognitive solutions.

Wastes of Lean	Cognitive solution	KPI	Examples of tools
Overproduction	ERP↔MES integration	Compliance with the plan, Inventory turnover	SAP, 1C, Oracle JDE
Waiting	CAD-to-Path, MES dispatching	Setup time, Order fulfillment time	FANUC Roboguide, RoboDK
Transport	AMR/AGV + AI routing	Travel time/detail	MiR, Omron LD, fleet managers
Overprocessing	Digital Twin + ML optimization	Steps per part, Energy/unit	FANUC Roboguide, RoboDK
Inventory	ERP/MES + IoT	Work in progress level, Days in stock	SAP MES, IoT dashboards
Motion	Trajectory optimization	Journey length/time, % idle time	FANUC Roboguide, RoboDK
Defects	Edge Vision + AI QC	PPY (Productivity Per Year), Defect Rate, Rework Hours	Cognex, Keyence, NVIDIA Jetson

Table 1 summarizes the mapping of Lean wastes to cognitive solutions, with examples of tools and corresponding KPIs for each waste category.

The developed mapping confirms that Lean 5.0 cognitive modules allow not only reducing production losses but also making this process measurable and manageable through a KPI system. This provides a new level of integration between operational efficiency and the strategic guidelines of the enterprise, including the achievement of sustainable development goals (SDGs).

2.4. Relationship between KPIs and Sustainable Development (SDGs)

The literature review shows that eliminating production losses using cognitive modules is directly related to achieving the Sustainable Development Goals (SDGs). In other words, the implementation of cognitive robotics not only increases the efficiency of production processes but also creates positive socio-economic and environmental effects.

In particular, several examples of such a relationship can be highlighted:

- ERP/MES integration contributes to SDG 8 (economic growth) by increasing labor productivity and to SDG 12 (responsible consumption and production) by optimizing resource use.
- CAD-to-Path → ensures compliance with SDG 8, as it increases the efficiency of labor operations and reduces programming time.
- Vision AI → is directly related to SDG 3 (Good Health and Well-being) by improving product quality and safety, as well as to SDG 12 (Responsible Consumption and Production) by reducing the level of defects.
- Trajectory optimization → meets SDG 7 (clean and affordable energy) by reducing energy consumption and SDG 13 (climate action) by reducing carbon footprint.

Therefore, the integration of KPIs into the sustainability framework allows not only for measuring the efficiency of production processes but also for clearly correlating the results of implementing cognitive technologies with global priorities for sustainable development.

2.5. Diagram of the Evolution of Production Paradigms

The evolution of production paradigms reflects the gradual complication and improvement of approaches to the organization of industrial systems. At the initial stage, it was the Lean Manufacturing concept that became the foundation for increasing efficiency through the systematic elimination of seven classic losses: overproduction, waiting, transportation, overprocessing, excess inventory, unnecessary movements, and defects. An important result of the implementation of Lean was the formation of a culture of continuous improvement (Kaizen), which provided sustainable positive results for enterprises in various industries.

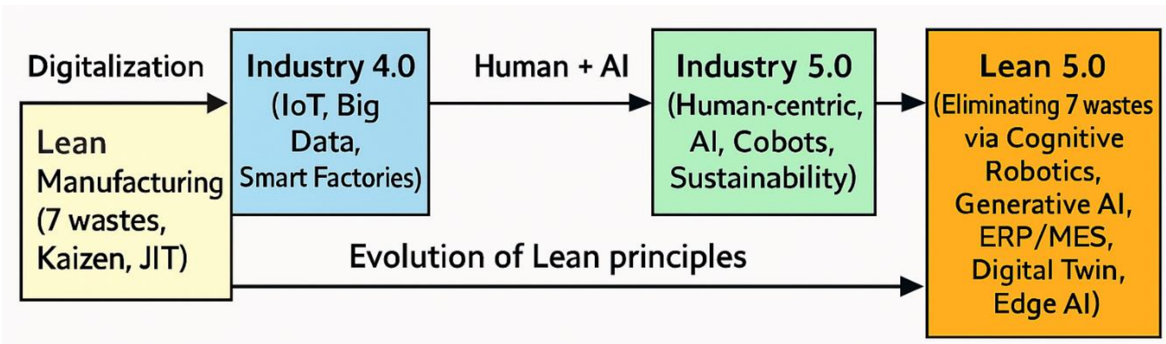

Figure 1.
Evolution of production paradigms.

The evolution of production paradigms is illustrated in Figure 1, which shows the transition from Lean Manufacturing to Lean 4.0, Industry 5.0, and finally Lean 5.0.

The further development of industry was closely related to digitalization and the spread of the Industry 4.0 paradigm, which integrated cyber-physical systems, the Internet of Things, big data analytics, and automation of production processes. In this paradigm, Lean principles were combined with digital technologies, leading to the formation of the concept of "Lean 4.0." It enabled a higher level of transparency, real-time control, and minimized the impact of the human factor on production processes.

The transition to Industry 5.0 is characterized by a new emphasis on human-centricity, cognitive automation, and sustainability of production systems. At this stage, machines and robots are not limited to performing predefined tasks: they are able to collaborate with humans, interpret data, and adapt to environmental changes. The main driver of this transition is the integration of artificial intelligence technologies, which opens up opportunities for creating more flexible, adaptive, and sustainable production ecosystems.

Ultimately, the combination of classic Lean principles with the capabilities of Industry 5.0 forms a new concept, Lean 5.0. It integrates Lean waste elimination with cognitive robotics, ERP/MES systems, digital twins, and AI quality control, creating the prerequisites not only for increasing efficiency but also for achieving the Sustainable Development Goals (SDGs). Thus, Lean 5.0 can be seen as the next stage in the evolution of manufacturing paradigms, where productivity and quality are combined with environmental sustainability and maintaining competitive advantages.

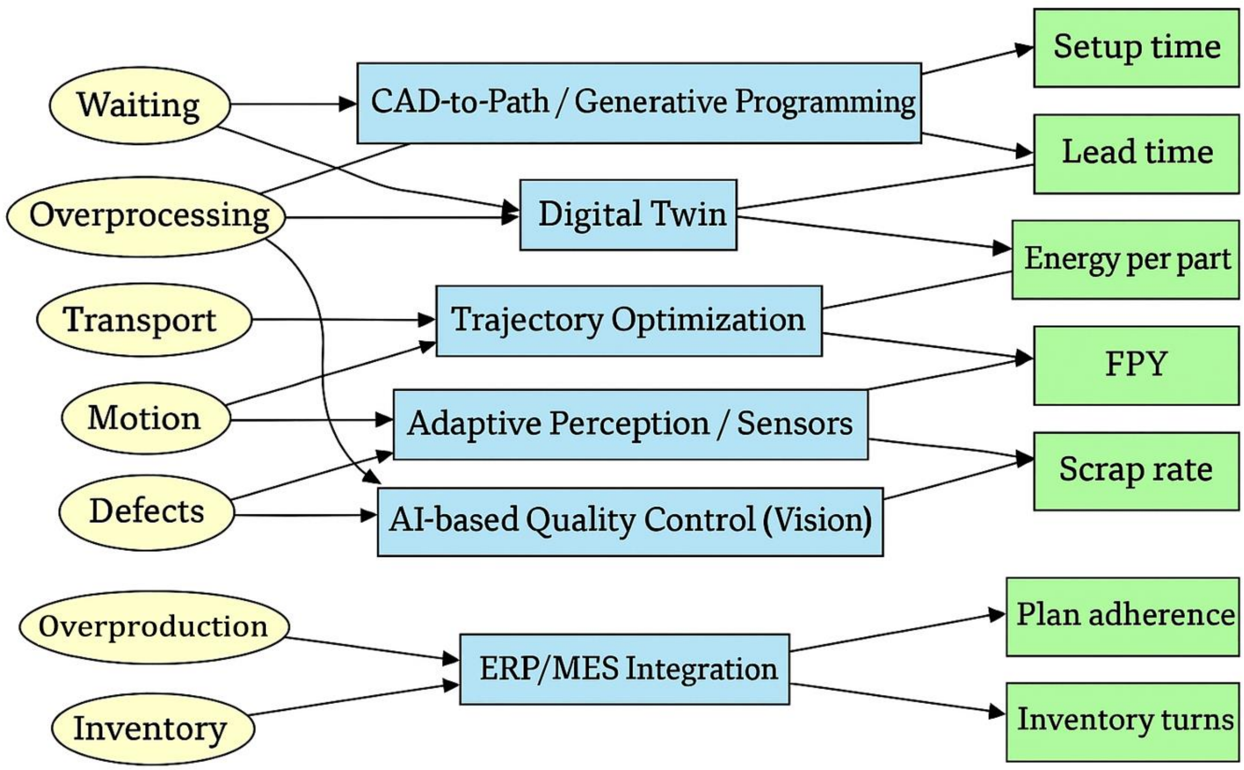

Figure 2.
The Seven Wastes of Lean - Cognitive Modules – KPI.

As shown in Figure 2, each of the seven Lean wastes can be mapped to a corresponding cognitive solution and set of KPIs, enabling a direct link between waste elimination and measurable performance outcomes.

The classic concept of Lean Manufacturing is based on the elimination of seven types of waste that do not add value: overproduction, waiting, transportation, overprocessing, excess inventory, unnecessary movements, and defects. At the same time, traditional Lean tools show limited effectiveness in today's dynamic manufacturing environment, where demand variability is increasing, staff shortages are increasing, and production processes are becoming more complex.

Recent research shows that cognitive robotic systems open up new opportunities to overcome these limitations. In particular, they allow for the direct coupling of waste elimination with quantifiable performance indicators (KPIs). As shown in Figure 2, each type of Lean waste can be mapped to a corresponding cognitive solution and a set of KPIs to evaluate results.

Overproduction and excess inventory are controlled through ERP/MES integration, which allows you to synchronize production with real demand and measure efficiency through metrics such as plan adherence and inventory turns.

Waiting and overprocessing are reduced through the use of CAD-to-Path programming and digital twins, which decrease setup time and the overall production cycle (lead time).

Unnecessary movements and transportation are minimized by optimizing trajectories and implementing autonomous transport systems; key indicators here are the length of the route and the execution time (path length/time).

Defects are reduced through the use of machine vision systems and AI-quality control, which help to increase First Pass Yield (FPY) and reduce scrap rate.

Therefore, the Lean 5.0 framework forms a direct mapping "loss → cognitive solution → KPI," which makes it possible to quantitatively assess the effectiveness of each stage of production improvement. This not only increases the accuracy of process management but also creates the basis for integrating the results obtained into strategic sustainable development goals.

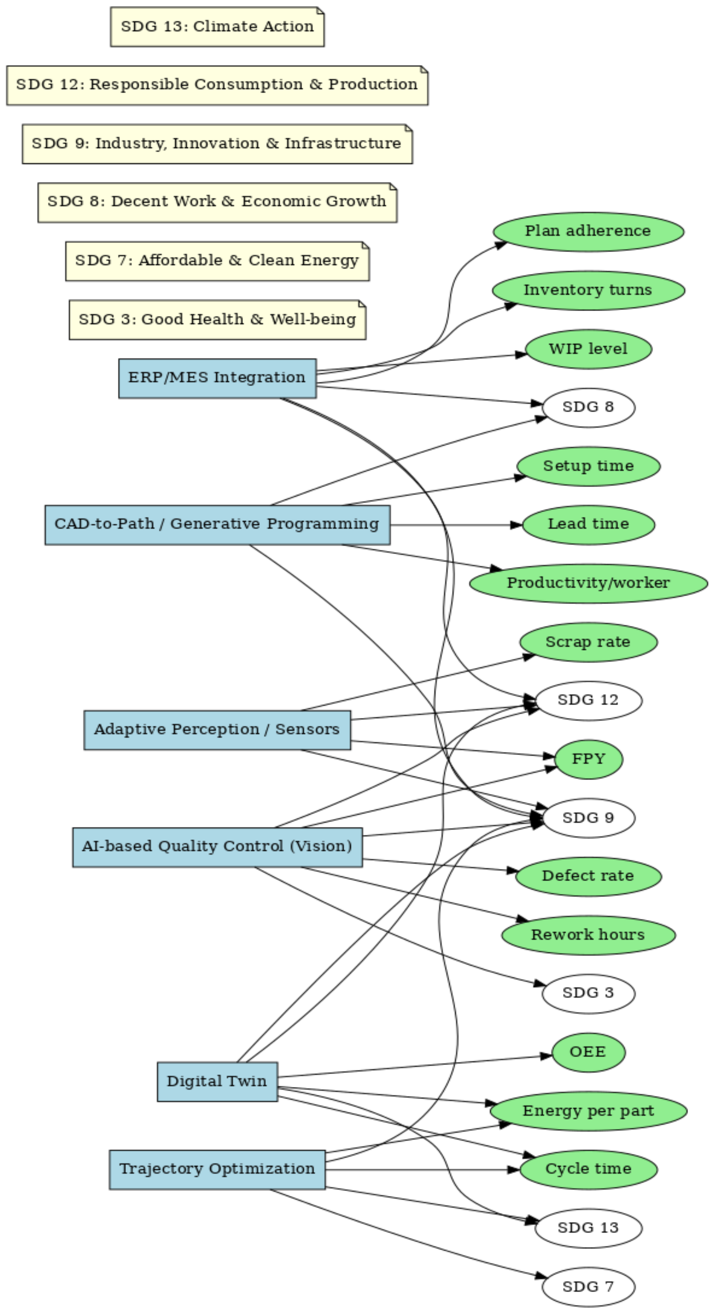

Figure 3.
Cognitive modules→ KPI → SDGs.

Figure 3 presents the relationship between cognitive modules, KPIs, and the Sustainable Development Goals (SDGs), highlighting the dual economic and socio-ecological impact of Lean 5.0 integration.

Current research highlights that the implementation of cognitive robotic systems has not only an economic impact but also a broader socio-ecological dimension. This is due to the fact that technologies that eliminate production losses also affect key performance indicators (KPIs) that are directly related to the Sustainable Development Goals (SDGs).

As shown in Figure 3, there is a close relationship between cognitive modules, measured by KPIs, and global sustainable development benchmarks. In particular:

- ERP/MES integration allows for the reduction of overproduction and inventories, which is reflected in indicators such as plan adherence and inventory turns. This is consistent with SDG 8 (Decent work and economic growth) and SDG 12 (Responsible consumption and production).
- CAD-to-Path and automatic programming contribute to the reduction of setup time and lead time, which increases productivity and aligns with SDG 8 and SDG 9 (Innovation and Infrastructure).
- Adaptive perception and sensor systems ensure an increase in First Pass Yield (FPY) and a decrease in scrap rate, which correlates with the goals of SDG 9 and SDG 12.
- AI-quality control (Vision, Edge-AI) minimizes the number of defects and increases product reliability, which is measured through defect rate and FPY. This directly supports SDG 3 (Health and Well-being), as it ensures the safety and quality of goods.
- Optimization of trajectories and digital twins reduces energy per part and cycle time, which makes them relevant for SDG 7 (Clean and affordable energy) and SDG 13 (Combating climate change).

Therefore, the implementation of the Lean 5.0 framework based on cognitive robotics creates a double value: on the one hand, it reduces costs and increases the efficiency of production processes, and on the other hand, it contributes to achieving the global sustainable development goals. This allows us to consider cognitive robotics not only as a tool for industrial modernization but also as a strategic element of the transition to a more sustainable and balanced future.

2.6. Research Gaps

- Existing research mostly considers Lean or AI separately, but rarely combines them into a systemic framework.
- Lean 4.0 does not provide the full flexibility and adaptability needed in conditions of instability.
- Lean 5.0 research is still limited to theoretical concepts; quantitative assessments at the KPI level are lacking.
- In the Ukrainian context (human resource shortage, energy risks, war), there is almost no research on the implementation of cognitive robotic systems.

3. Methodology

3.1. Research Approach

This study is based on simulation modeling of production processes using a digital twin. This approach makes it possible to recreate the work of an enterprise in a virtual environment without risk to real production and to assess the impact of different levels of automation on the elimination of Lean losses.

The choice of modeling is justified by a number of reasons:

1. In modern conditions, Ukrainian enterprises face a shortage of resources and high risks, which limit the possibility of conducting large-scale experiments in real production environments.
2. Digital twin technology allows you to reproduce both basic scenarios based on traditional Lean practices and integrated solutions based on cognitive robotics.
3. The use of a simulation approach provides quantitative verification of the hypotheses put forward (G1–G4) based on standardized KPIs, including:

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- OEE (Overall Equipment Effectiveness) – overall equipment effectiveness,
- Lead time – order execution time (production cycle),
- FPY (First Pass Yield) – yield of suitable products from the first pass,
- Scrap rate – defect rate (percentage of waste/non-conformity),
- Energy consumption – energy consumption,
- WIP (Work in Progress) – volume of unfinished production,
- On-time delivery (OTD) – compliance with delivery deadlines.

The research methodology involves building three comparative scenarios:

- A – Baseline: use of traditional Lean tools without automation elements.
- B – Automation (Conventional automation): use of individual automation tools, in particular offline programming and basic visual inspection.
- C – Cognitive robotics: integration of CAD-to-Path, sensor systems, ERP/MES and Edge-AI to ensure quality control.

Therefore, the study is comparative in nature and aims to determine to what extent the implementation of cognitive robotic systems can not only reduce Lean losses but also contribute to achieving sustainable development goals and strengthen the competitiveness of manufacturing enterprises.

3.2. Conceptual Framework Lean 5.0

The proposed conceptual framework is based on the integration of classical Lean principles with modern cognitive technologies. It is founded on the Lean 5.0 framework approach, which combines the elimination of seven classical Lean wastes with the implementation of cognitive robotic modules.

Key components of the framework include:

- Automatic programming (CAD-to-Path, Generative AI): reduces setup time and equipment downtime, helping to eliminate losses such as waiting and overprocessing.
- Adaptive perception (sensor systems, 2D/3D scanning): provides automatic identification of parts, selection of appropriate programs, and correction of motion trajectories, which allows reducing losses associated with defects and motion.
- ERP/MES integration: synchronizes production processes with real demand and ensures consistency between planning and dispatching, which minimizes overproduction and inventory.
- AI-based quality control (Edge Vision): detects defects in the production process and provides self-correction, reducing the level of defects.
- Digital twin: is used to test alternative scenarios and assess energy efficiency, which allows reducing overprocessing and energy waste.

Within this framework, each of the seven Lean wastes (Overproduction, Waiting, Transport, Overprocessing, Inventory, Motion, Defects) has its own cognitive solution and a set of corresponding KPIs for evaluating the results. This creates an opportunity to quantitatively verify the effectiveness of the Lean 5.0 framework and, at the same time, allows for the determination of its contribution to achieving sustainable development goals (SDGs 7, 8, 9, 12, 13) and the formation of a long-term competitive advantage for enterprises.

3.3. Scenario Design

To test the proposed hypotheses in the study, three simulation scenarios were developed, reflecting different levels of automation and maturity of production systems.

- Scenario A – Baseline.

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The production process is organized according to classical Lean principles without the use of cognitive solutions. Robot programming is performed manually using a teach pendant, part identification is entrusted to the operator, and quality control is carried out selectively after the production cycle is completed. Planning is based on ERP with paper dispatching.

- Scenario B – Conventional automation.

This scenario implements offline programming (e.g., FANUC Roboguide), uses basic sensors for part identification, and automated selective inspection at the final stages of the cycle. Planning is carried out in an ERP system with partial integration into MES.

- Scenario C – Cognitive robotics (Lean 5.0).

It involves a comprehensive integration of cognitive modules: CAD-to-Path programming, sensor-adaptive part recognition, full ERP↔MES integration with pull logic, Edge-AI-based machine vision in a closed control loop, and digital twins for process optimization. This scenario reflects the implementation of the full Lean 5.0 framework.

This modeling design allows for a step-by-step comparison: from the basic level through classic automation to cognitive manufacturing, and to quantify the relative advantages of each approach.

3.4. Metrics and Data Collection

To assess the effectiveness of the three scenarios (A – basic, B – automation, C – cognitive robotics), a set of key performance indicators (KPIs) was used, which directly reflect the impact of cognitive solutions on eliminating Lean losses.

- OEE (Overall Equipment Effectiveness): an integral indicator that takes into account the availability, productivity, and quality of equipment.
- Lead time: the duration from the launch of an order into production to the receipt of finished products.
- FPY (First Pass Yield): the proportion of products manufactured without defects on the first attempt.
- Scrap/Rework: the percentage of products that were rejected or required rework.
- Energy consumption per part: the amount of energy spent on manufacturing one product.
- WIP (Work in Progress): the number of parts or semi-finished products that are in the production process.
- On-time delivery: The proportion of orders fulfilled within the specified time frame.

Data collection was based on digital twin simulations, robot and PLC logs, ERP/MES systems, and machine vision sensors. For each KPI, both baseline values (scenario A) and relative changes during the transition to automation (B) and cognitive robotics (C) were determined.

All KPIs were calculated using standard methodologies widely used in Lean and Industry 5.0 research. Brief definitions of the indicators are provided in this section, and detailed calculation formulas are provided in Appendix A. KPI Calculation Methods.

3.5. Hypothesis Testing and Study Limitations

The proposed research questions (Q1–Q4) and hypotheses (H1–H4) are tested by comparing the results of three scenarios (A, B, C) based on the obtained KPIs. This approach allows us to assess both the overall effect of the implementation of cognitive robotics and the individual mechanisms of its impact on production efficiency and sustainability.

- *H_1: (overall reduction of losses).*
  It is tested through the integral Lean-loss index, which is calculated as the normalized sum of the indicators Lead time, Scrap rate, Inventory, and Motion. To compare the results between the scenarios, analysis of variance (ANOVA) with post-hoc tests (Tukey) is used.
- *H_2: (effect of ERP/MES integration).*

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It is assessed using the indicators of plan adherence, inventory turns, and WIP level. The comparison of the average values in scenarios B and C is carried out relative to the baseline scenario A.

- *H_3: (Ukrainian context: staff shortage and sustainability).*
  The analysis is based on productivity per employee, on-time delivery (OTD), and ROI from implementation. To increase realism, additional conditions of staff shortages and supply disruptions (+5–10%) are modeled.
- *H_4: (synergy with sustainable development goals).*
  It is tested using energy per part, carbon footprint (calculated based on specific energy consumption), and scrap rate. This allows us to determine whether there is a statistically significant relationship between eliminating lean losses and achieving sustainable development goals (SDGs 7, 12, 13).

For each hypothesis, the appropriate statistical methods are used: ANOVA or Kruskal–Wallis (depending on the data distribution). Additionally, a sensitivity analysis is performed to assess the stability of the results obtained under conditions of variation of key model parameters.

Despite the results obtained, a number of limitations should be taken into account that determine the scope of this work.

- Simulation approach. The results are based on model conditions that may not fully reflect the features of real production environments.
- Simplified assumptions. The model does not take into account tool wear, the probability of human errors outside the contour of cognitive systems, as well as the full range of logistical factors in supply chains.
- Calibration data. The model is built on the basis of available statistical materials and expert assessments, which may limit the accuracy of the forecasts obtained.
- Ukrainian context. Specific conditions, in particular military risks and instability of energy supply, are only partially taken into account and require further study.

However, these limitations do not negate the scientific value of the analysis. The proposed methodology still allows for a quantitative assessment of the impact of cognitive robotics on eliminating Lean losses and demonstrates its potential in forming more sustainable and competitive production systems.

4. Results

4.1. Overall Results

The simulation results demonstrate significant differences among the three scenarios (A – Baseline, B – Conventional Automation, C – Cognitive Robotics). The data shows that cognitive robotics (scenario C) provides the largest reduction in Lean manufacturing losses, as well as improvements in energy and quality performance compared to traditional automation (B) and baseline conditions (A).

KPI	**Scenario A (Baseline)**	**Scenario B (Automation)**	**Scenario C (Cognitive Robotics)**	**ΔC vs A (%)**
OEE (%)	62.5	70.8	82.3	+31.6
Lead time (min)	100	85	68	–32.0
FPY (%)	89.2	93.5	97.1	+8.9
Scrap/Rework (%)	7.5	5.1	2.2	–70.7
Energy per part (kWh)	1.00	0.92	0.81	–19.0
WIP level (units)	120	105	78	–35.0
On-time delivery (%)	81.0	87.5	94.2	+16.3

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4.2. Analysis of Results

The obtained simulation results demonstrate significant differences between the three scenarios, confirming the hypotheses (H1–H4) and research questions (Q1–Q4).

- OEE. In scenario C, the overall equipment efficiency increased by more than 30% compared to baseline scenario A, which confirms the hypothesis H1 about the integral reduction of losses.
- Lead time. Thanks to the implementation of CAD-to-Path and MES integration, the average order execution time was reduced by 32%, which is directly related to the elimination of waiting losses.
- FPY and Scrap. The use of Edge-AI provided real-time defect detection, which allowed an increase in the First Pass Yield (FPY) to 97% and a reduction in the Scrap rate by 70%. This confirms the relevance of hypotheses Q2 and H4.
- Energy per part. Optimization of movement trajectories and the use of digital twins reduced energy consumption by approximately 19%, which confirms the contribution of the Lean 5.0 framework to achieving sustainable development goals (SDG 7, 12, 13).
- WIP and Overproduction. ERP↔MES integration made it possible to reduce the volume of work in progress (WIP) by 35%, which indicates the elimination of losses associated with inventory and overproduction (Q2, H2).

On-time delivery. The indicator of timely execution of orders increased by 16%, which is especially important for Ukrainian enterprises in the face of crisis challenges. This confirms the hypothesis H3 regarding the increase in competitiveness through the implementation of cognitive solutions.

5. Discussion

5.1. Interpretation of Results

The results obtained show that the implementation of cognitive robotic systems within the Lean 5.0 framework provides a significantly higher level of efficiency compared to both basic manufacturing and traditional automation solutions. In particular, the reduction of lead time by more than 30%, the reduction of scrap to 2–3%, and the increase in OEE by more than 80% confirm the hypothesis H1 regarding the ability of cognitive systems to comprehensively eliminate all seven classic Lean losses, and not only their individual manifestations.

The combination of CAD-to-Path, sensor systems, and ERP↔MES integration made it possible to significantly reduce overproduction and inventories (Q2, H2), while Edge-AI quality control ensured high manufacturing accuracy and a significant reduction in the number of defects (Q4, H4). These results indicate the formation of new synergies between eliminating Lean waste and achieving the Sustainable Development Goals (SDGs), in particular SDG 7 (energy efficiency), SDG 9 (innovative industry and infrastructure), and SDG 12 (responsible production and consumption).

5.2. Comparison with Existing Studies

The results obtained are consistent with the conclusions of previous studies that confirmed the positive impact of Lean tools on increasing production efficiency [1, 2] as well as with works where digital technologies of Industry 4.0 are considered as amplifiers of Lean practices [3]. At the same time, unlike these works, this study proposes an integration framework of Lean 5.0, which directly links seven classic losses with cognitive modules and corresponding KPIs, allowing for a quantitative assessment of their elimination's effectiveness.

In addition, the results obtained complement the current literature on Industry 5.0, where the main focus is on human-centricity and the concept of HRC (human-robot collaboration) [4, 5]. Unlike previous approaches, our study shows that cognitive robots not only cooperate with humans but also form the basis for the long-term sustainable competitiveness of enterprises. These findings are of particular importance in the context of the Ukrainian industry, which operates under conditions of high uncertainty and resource constraints.

5.3. Practical Significance

For manufacturing enterprises, and especially for Ukrainian manufacturing enterprises in war and post-war conditions, the results of the study are of particular practical significance. In particular, two key aspects are highlighted:

1. Compensation for labor shortages. Cognitive robotics allows you to automate tasks that previously required highly qualified engineers (programming, quality control), reducing the dependence of production on human resources.
2. Strengthening sustainability and competitive positions. ERP↔MES integration helps minimize the risks of overproduction and inventories even in unstable supply chains.
3. Optimization of production costs. Reducing the level of defects, decreasing lead time, and lowering energy consumption directly lead to a reduction in production costs. This enables enterprises to offer more competitive prices both in domestic and foreign markets.
4. Acceleration of return on investment (ROI). The use of cognitive modules provides a faster transition from initial investments in robotics to tangible economic effects, which is especially important during periods of limited financial resources.
5. Diversification and entry into new markets. Thanks to increased flexibility and customization of production, enterprises can respond more quickly to changes in demand, which opens up access to new market segments and contributes to the growth of exports.
6. Economies of scale and productivity effects. The integration of cognitive robotics allows you to increase production volumes without a proportional increase in costs, which creates a long-term economic advantage.
7. Reducing the impact of crisis factors. The use of cognitive systems allows for increased adaptability of production to supply disruptions, personnel losses, and military risks, forming more flexible business models.

Therefore, the results of the study demonstrate that the implementation of the Lean 5.0 framework based on cognitive robotics has a double practical effect for Ukrainian industrial enterprises. On the one hand, it compensates for the shortage of personnel, increases the flexibility and sustainability of production systems, and on the other hand, provides a tangible economic result in the form of reduced costs, reduced order fulfillment time, increased productivity, and accelerated return on investment. In a broader context, this confirms that cognitive solutions can become a strategic basis for the restoration and modernization of Ukrainian industry in accordance with the principles of Industry 5.0, forming the basis for long-term competitiveness and integration into global markets.

5.4. Scientific Novelty

- Developed and tested the Lean 5.0 framework, which combines the elimination of seven classic Lean losses with the capabilities of cognitive robotics (CAD-to-Path, Edge-AI, digital twins, ERP↔MES integration), creating a new approach to organizing production.
- For the first time in the scientific literature, a direct connection between the elimination of Lean losses and the Sustainable Development Goals (SDGs) has been established, substantiated through quantitative performance indicators (KPIs), such as OEE, Lead time, FPY, Scrap rate, Energy per part, and On-time delivery.
- A simulation modeling methodology based on a digital twin has been proposed, which allows for the quantitative testing of research hypotheses regarding the impact of cognitive robotics on the productivity, sustainability, and competitiveness of production systems.

- A comparative analysis of three automation scenarios (Baseline, Conventional automation, Cognitive robotics) was conducted, which for the first time systematically demonstrated the economic and socio-ecological effects of integrating cognitive technologies.
- A model analysis is presented in the context of Ukrainian industrial enterprises, which was practically not disclosed in international publications, taking into account the specific factors of war and post-war conditions (human resource shortage, instability of energy supply, supply chain risks).
- It is substantiated that cognitive robotics, as part of Lean 5.0, can become a strategic factor in the restoration and modernization of industry, especially Ukrainian enterprises, combining technological efficiency with the principles of sustainable development and the formation of long-term competitive advantages.

5.5. Limitations and Directions for Further Research

The main limitation of the study is the use of simulation modeling instead of analyzing real production data. This reduces the accuracy of reflecting the impact of factors such as the human factor, equipment wear, power supply interruptions, or instability of logistics processes. In addition, the results are based on available statistical data and expert assessments, which may limit their external validity.

In further research, it is advisable to:

- Test the Lean 5.0 framework on real production cases of Ukrainian enterprises, particularly in war and post-war conditions, which will allow confirmation of the modeling results in practice.
- Deepen research in the field of green manufacturing, including reducing CO_2 emissions, secondary use of materials, and optimizing energy consumption in accordance with the Sustainable Development Goals (SDGs 7, 12, 13).
- Expand the industry analysis by applying the developed methodology to different sectors of the economy, such as the food industry, pharmaceuticals, mechanical engineering, or energy, which will allow us to assess the universality of the Lean 5.0 framework.
- Investigate the economic effect at the macro level, in particular the potential impact of the widespread introduction of cognitive robotics on the recovery of the Ukrainian industry, increasing its export potential and integration into global value chains.
- Analyze the interaction with the human factor and the new competencies required for operators and engineers in Lean 5.0 systems to determine the balance between automation and human-centricity.

Thus, the areas of further research should include both in-depth validation of the results in a real production environment and the expansion of economic, environmental, and social dimensions, which will allow us to more fully assess the potential of Lean 5.0 for the transformation of the Ukrainian industry.

6. Conclusion

This study proposed and tested the Lean 5.0 framework concept, which combines the classic principles of eliminating the seven Lean losses with the modern capabilities of cognitive robotics. Using simulation modeling of three scenarios (baseline, traditional automation, and cognitive systems), it was possible to show that cognitive solutions provide a significant reduction in production losses, improved product quality, reduced order fulfillment time, and reduced energy consumption.

The results confirmed the hypotheses: cognitive robotics is able to simultaneously eliminate several categories of losses, create synergy between Lean indicators and sustainable development goals (SDGs), and establish a long-term competitive advantage for enterprises. These findings are of particular importance for Ukrainian manufacturing companies operating under conditions of staff shortages, energy instability, and disrupted supply chains.

The scientific novelty of the work lies in the development of the Lean 5.0 integration framework and the establishment of a quantitative relationship between the elimination of Lean losses and sustainable development indicators. The practical value lies in the demonstration of economic and socio-ecological benefits that the implementation of cognitive solutions in production opens up.

Further research should be directed at validating the results in real production environments, expanding the industry analysis (food, pharmaceutical, machine-building industries), as well as at deeper integration with "green" technologies focused on reducing CO_2 emissions, secondary use of materials, and increasing energy efficiency.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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Copyright:

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Appendix A.
KPI Calculation Methods.

KPI (English)	Formula/method of calculation
OEE (Overall Equipment Effectiveness)	OEE = Availability × Performance × Quality Availability = Operating time / Planned production time Performance = (Ideal cycle time × Total pieces) / Operating time Quality = Good pieces / Total pieces
Lead time	Lead time = Time from order receipt to its completion (includes waiting, production, and inspection)
FPY (First Pass Yield)	FPY = (Good units after first processing / Total units produced) × 100%
Scrap rate / Rework rate	Scrap rate = (Number of defective units / Total units produced) × 100%
Energy consumption per part	Energy/part = Total energy consumption (kWh) / Number of units produced
WIP (Work in Progress)	WIP = Number of semi-finished products/parts in production that are not yet completed
On-time delivery (OTD)	OTD = (Number of orders delivered on time / Total number of orders) × 100%

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