



Baština Akademije nauka i umjetnosti Bosne i Hercegovine

SMART MANUFACTURING ON THE HORIZON: A Conceptual Shift from Industry 4.0 to Industry 5.0: Industrija

Karabegović, Isak

2026

Academy of Sciences and Arts of Bosnia and Herzegovina

<https://bastina.anubih.ba/handle/123456789/875>

Preuzeto s Baštine Akademije nauka i umjetnosti Bosne i Hercegovine

<https://bastina.anubih.ba/>

Dark Factory vs. Humanoid Factory: Two Development Directions of Industrial Automation in Comparison

Viktorio Malisa^{*1}

Abstract: *Industrial automation is currently shaped by two complementary development paths: the highly standardised, fully autonomous Dark Factory and the Humanoid Factory, in which humanoid robots serve as flexible automation components within existing production environments. While both concepts pursue unmanned manufacturing, they differ fundamentally in flexibility, infrastructure compatibility, and technological maturity. Dark-factory approaches are already established in several industries, whereas no productive systems relying entirely on humanoid robotics exist to date.*

This study compares both paradigms through a systematic literature review and a conceptual classification within the context of industrial production systems. The findings show that humanoid robots can address automation challenges in areas previously considered difficult to automate, positioning them as a complementary technology rather than a competing one. At the same time, significant research and development needs emerge at the intersection of autonomy, adaptability, and safety.

The analysis concludes that a fully Humanoid Factory is not feasible in the short-to-medium term due to technological immaturity and the absence of harmonised safety and certification frameworks. However, evidence suggests that hybrid production models are beginning to emerge, in which humanoid robots are gradually integrated into dark-factory environments to enhance adaptability, resilience, and variant-rich production capabilities.

Keywords: *Dark Factory, Lights-Out Manufacturing, Humanoid Factory, Humanoid Robot, Industry 5.0*

1. Introduction

In the wake of digital transformation, industrial production is undergoing a fundamental paradigm shift. Shortages of skilled workers, rising costs and the desire to achieve optimum efficiency are prompting the development of two contrasting yet forward-thinking approaches to automation. On the one hand, there is the concept of the 'dark factory'. These fully automated production facilities operate without human staff, require neither lighting nor air conditioning, and are based on a rigid, highly integrated network of traditional industrial and logistics systems. In contrast, humanoid robotics is emerging as a

^{*1}F-AR Förderung der Automation und Robotik, Wien, Austria
E-mail: malisa@f-ar.at

flexible, anthropomorphic approach to automation. These robots are designed to integrate into existing work environments and use human-optimised tools, thus eliminating the need for significant infrastructure changes.

The concept of the 'Dark Factory' involves eliminating all human involvement on the factory floor. Meanwhile, the field of humanoid robotics aims to replicate human flexibility and physical capabilities with precision. Integrating these approaches into existing industrial production systems raises profound questions, as do the associated technological, economic, and strategic implications. The focus then shifts to the challenges of industrialising humanoid robots and exploring the potential of combining these two automation concepts to create hybrid architectures.

According to the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), a Dark Factory is defined as a fully automated production environment without permanent human presence, supported by autonomous material logistics, self-monitoring processes, and AI-based error detection. Fraunhofer positions this model as the final evolutionary stage of Industry 4.0 automation. [5]

This thesis conducts a comparative analysis of the development trajectories of the Dark Factory and humanoid robotics within an industrial context. Examining how well both fulfil modern core requirements such as human-centredness, sustainability, and systemic resilience, the study is conducted from an Industry 5.0 perspective. Based on this analysis, a criteria matrix is developed to inform future sustainable automation strategies.

2. Classification: Production Processes and Level Of Automation

2.1 The Process Industry As The Original 'Dark Factory'

The process industry, which includes the chemical, petrochemical, pharmaceutical, food processing and steel sectors, has been gradually automated since the 1960s. To a particularly significant extent, this process has occurred since the 1970s and 1980s, effectively turning it into a 'dark factory' through the use of digital control technology and, later, networked, software-based systems. Refineries, chemical plants and breweries now operate largely without human intervention: raw materials flow in and products flow out, all controlled by Distributed Control Systems (DCS), Supervisory Control and Data Acquisition (SCADA) systems and Programmable Logic Controllers (PLC). The problem of continuous human-free production has been solved here for decades.

The key difference from discrete manufacturing lies in the nature of the product: the process industry generates continuous streams of liquids, gases or bulk materials. Human tasks are limited to monitoring, maintenance, and dealing with exceptional situations, and even these are increasingly being carried out remotely.

2.2 Hybrid Process Chains: Transitioning From Continuous to Batch Production

Fully automated process chains form a distinct category. In these chains, continuous manufacturing processes transition seamlessly into the handling of discrete items with no interruption to the flow of the process and no human intervention.

Typical examples:

- Plastic film production: cutting > winding onto rolls > automatic palletising.
- Liquid production (e.g. water, beer, milk, juice): filling > capping > labelling > packaging > palletising.
- Dough or batter production: portioning > baking/shaping > packaging > cartoning.
- Wire or tube drawing: depositing > bundling > packaging.

These fully integrated production lines have been utilised in industry since the 1980s and 1990s. In accordance with the definition of lights-out operation, these factories are effectively 'Dark Factories'. Despite the continuous optimisation of their underlying systems in terms of throughput, process quality and digital connectivity, these production lines have become the established standard in automation technology.

2.3 Discrete Manufacturing as a Driving Force for Innovation

The focus of automation is therefore on discrete manufacturing, particularly in areas where product variety, complexity and frequent product changes push traditional automation approaches to their limits or beyond.

As shown in Table 1, the term 'dark factory' is a novel concept, particularly in the context of discrete mass production. The gap in diverse and flexible discrete manufacturing is to be filled by humanoid robots. Currently, this need is met by stationary industrial robots, human-robot collaboration, and a shortage of skilled workers.

Table 1. Production systems and their level of automation in the context of the Dark Factory and the Humanoid Factory

Production systems	Examples	State of automation	Impact
Continuous process industry	Refineries, chemical industry, power stations	DCS/SCADA/PLC since the 1970s	Resolved for decades; ongoing networking and efficiency improvements
Hybrid process chain	Film extrusion >> Cutting >> Winding; Filling >> Sealing >> Palletising	Fully integrated lines, PLC-controlled	Automated since the 1980s/1990s – established Dark Factory
Discrete manufacturing (mass production)	Automotive press shops, pharmaceutical filling, semiconductors	Industrial robots, AGVs, AMRs	Dark Factory as an active optimisation target
Discrete manufacturing (variant production)	Small-batch assembly, customised assemblies, logistics	Shortcomings: too variable for stationary robotics, shortage of skilled workers	Target domain of the Humanoid Factory

3. Concepts and State of the Art

3.1 The Concept of the Dark Factory (Lights-out Manufacturing)

A dark factory, also known as lights-out manufacturing, is a production environment that requires no human intervention across multiple production cycles. The term derives from the fact that these systems can be operated without lighting, air conditioning or ergonomic adjustments when running in automatic mode. The primary technological foundation consists of standardised, networked machines, industrial robots, automated high-bay warehouses, driverless transport systems and autonomous mobile robots. The efficiency of such factories is linked to maximum standardisation and the elimination of human factors.

Conventional research has concentrated on the maintenance of process continuity and stability, predictive maintenance, and the mathematical optimisation of material flows. In a conventional Dark Factory architecture, there is a fully automated production area and a physically separate support area for human activities. Even in a dark factory, production cannot operate entirely without human involvement. In the autonomous production line (see Figure 1), materials such as granules, powder, paper bags, plastic tubes and empty pallets are processed automatically. Conveyor belts, packaging stations and robotic handling systems are employed to manage all process steps, culminating in the provision of a fully loaded pallet secured with stretch foil. The process is entirely automated, with no requirement for physical intervention by humans.

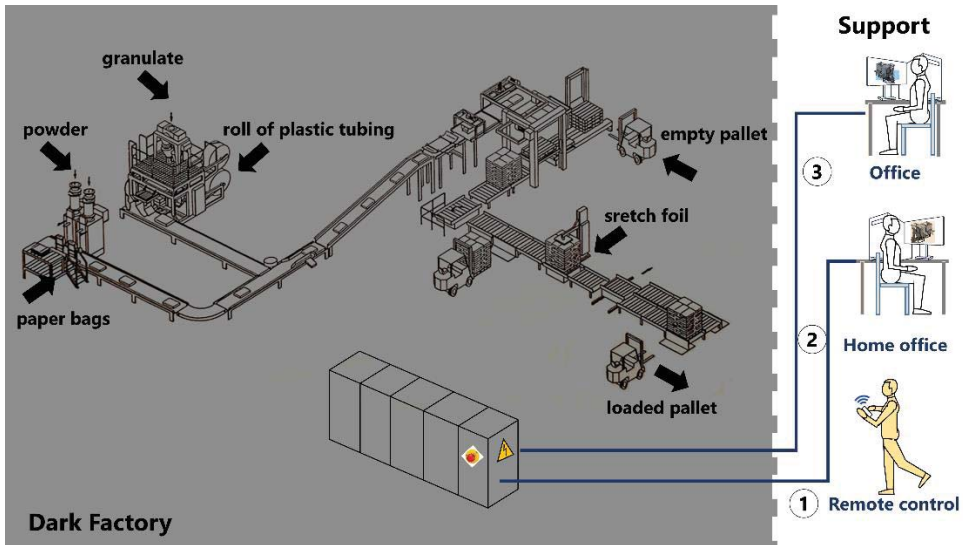


Figure 1. Schematic diagram of a Dark Factory

The permitted human roles in the 'Support' area outside the production hall (see Figure 1) are limited to the following:

- Remote control: remote access to machines and systems via mobile devices.
- Home Office: remote process monitoring and intervention.
- Office: overarching planning, analysis and control from a separate office area.

Therefore, all human activities take place outside the production area and are limited to monitoring, remote maintenance and management.

3.2 The Concept of the Humanoid Factory

In contrast, there is the Humanoid Factory approach. Based on the principle of anthropomorphic flexibility, this approach differs from the location-bound, specialised automation of the Dark Factory. A humanoid robot is a machine whose physique is modelled on the human body. This means that it has a head, a torso, two arms, hands, and two legs. The theoretical relevance of this approach stems from the concept of brownfield automation. Unlike traditional automation, where the factory environment is built around the machine, humanoid robotics enables a new approach: the machine is adapted to the factory environment. The robot should be able to adapt to a factory environment designed for humans.

Technologically, this development involves shifting towards artificial intelligence (AI), computer vision, and advanced sensor technology such as force-torque sensors and end-effectors that mimic human fine motor skills. Current research efforts focus primarily on the General-Purpose Robot (GPR). The term GPR is derived from general purpose AI (GPAI).

According to current theory, these robots are capable of learning various tasks without the need for complex programming, thanks to reinforcement learning and Large Behaviour Models (LBM). In a Humanoid Factory, humanoid robots perform human-like tasks and interact with other machines. Typical applications include collaborative work with industrial robots, order picking from shelves, material transport via AMRs (Autonomous Mobile Robots), and assembly work at traditional workstations. In line with the underlying principle, humanoid robots will take over the performance of human tasks, whilst the existing industrial infrastructure continues to be utilised. Whilst the Dark Factory automates the process, the Humanoid Factory automates human activity.

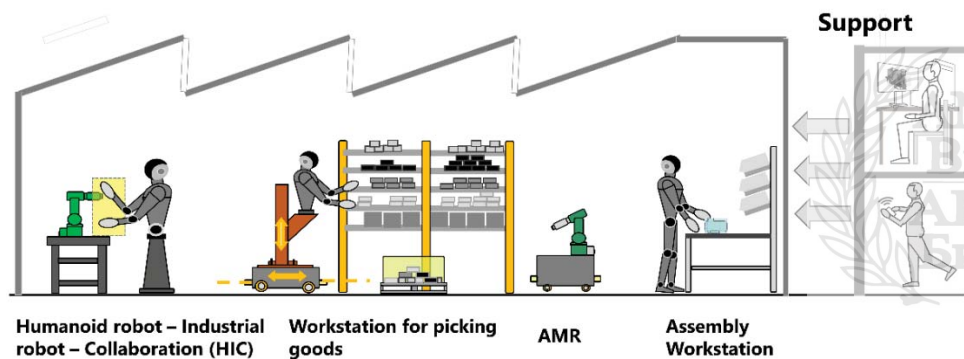


Figure 2. Schematic representation of a humanoid factory

As demonstrated in Figure 2, the Humanoid Factory concept involves the deployment of humanoid robots to perform tasks and interact with other machinery in a manner that emulates human behaviour. The figure illustrates the typical areas of application of AMRs, namely collaborative work with industrial robots, order picking, material transport, and assembly work at traditional workstations. The Humanoid Factory principle is elucidated as follows: the performance of human tasks is assumed by humanoid robots, with the existing industrial infrastructure remaining in use.

The term "Humanoid Factory" refers to a manufacturing environment in which human-like robots are responsible for key tasks. The product's unique selling point is its compatibility with existing infrastructure designed for humans. This encompasses tools, work surfaces, shelves and transport equipment, which can be utilised without modification due to their design to align with human body proportions.

Consequently, the paradigm is not oriented towards process standardisation, but rather towards adaptability. The objective of humanoid robots is to acquire new tasks through imitation, learning or natural language instructions, without the necessity for complex reprogramming.

3.3 Challenges in Implementing the ‘Humanoid Factory’

The current debate surrounding humanoid robots is characterised, above all, by a focus on hardware demonstrations and projected cost trends. However, the main obstacle to their widespread industrial use is the lack of regulatory standards. Although advanced technologies are being integrated into robotic systems, appropriate standards are lacking. Consequently, researchers must carry out risk assessments for their own developments and take appropriate measures to mitigate risks [13]. In this regard, it is crucial to integrate safety functions into the machines' control systems.

Humanoid robots are equipped with the following technologies:

- Bipedal platforms offering 20–40+ degrees of freedom for full-body manipulation;
- Multi-fingered robotic hands for heterogeneous grasping.
- Foundation models and large language models (LLMs) enable the robots to understand tasks and process instructions. These are large, pre-trained AI models that possess a broad understanding of language. They can interpret tasks, follow instructions, and adapt flexibly to new requirements without needing to be reprogrammed for each individual task.
- Imitation and reinforcement learning for robotics (RLfR): the robot learns through trial and error, i.e. it teaches itself to solve a specific task as effectively as possible.
- Edge AI and onboard inference enable real-time decision-making. AI models run on local processors within a robot. With onboard inference, the device performs the AI calculations itself. This allows the robot to make real-time decisions and react independently in milliseconds, even without an internet connection.
- SLAM (Simultaneous Localisation and Mapping) is a navigation technique used in dynamic environments. Robots use various sensors, such as cameras, LiDAR, radar and ultrasound, to map their constantly changing surroundings. As objects are moved and people walk around, the robot builds a map of its surroundings while determining its own position within them.)

Although humanoid robots themselves do not have a CE declaration of conformity, system integrators are incorporating them into manufacturing processes. As they are considered partly completed machinery, they must be fully safeguarded by external safety measures. These systems take over the safety-related functions, enabling the humanoid robot to operate as a non-safety-related module. This is only possible because there are currently no harmonised standards for dynamically stable industrial mobile robots. Work is underway to develop the ISO 25785-1 standard. This will apply to dynamically stable industrial mobile robots (DSIMRs), including humanoid robots.

In parallel to these European standardisation efforts, international bodies are increasingly recognising the urgency of establishing safety frameworks for dynamically stable robots. ASTM International has recently called for the rapid development of global safety standards for humanoid robots, warning that industrial deployments are progressing faster than the regulatory mechanisms needed to ensure safe operation [12]. This highlights that the challenges associated with integrating humanoids into industrial environments are not only technical but also regulatory, and that harmonised global standards will be essential for their safe and widespread adoption.

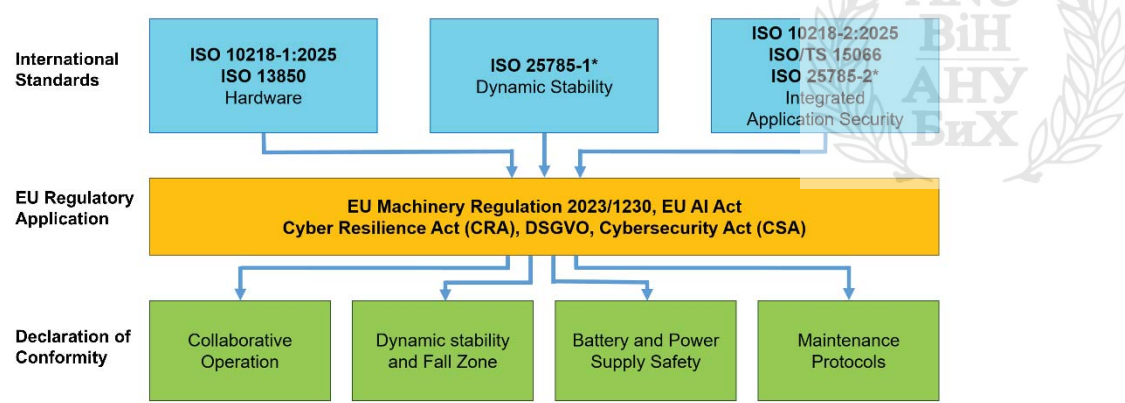


Figure 3. EU compliance framework for humanoid robots, in accordance with [10]

* Standards currently being drafted

Figure 3 provides an overview of the main EU regulations and standards currently in place for CE marking in robotics. As well as listing the adopted standards, it also lists those that are still under development. The latter include ISO 25785-1 and ISO 25785-2, which cover the integration of dynamically stable robots into automation systems.

A key difference between stationary industrial robots and humanoids is their behaviour during an emergency shutdown: industrial robots remain stationary and

in a safe state when the power is cut off, whereas humanoids collapse because their stability is actively maintained by motor control. Humanoids, on the other hand, collapse because their stability is actively maintained by motor control.

The concept of the 'Safe-Stopable Envelope' (SSE) addresses this issue by defining a state space. From this state, the robot can be reliably moved to a safe, minimum-risk position (Minimum Risk Condition, MRC) when an emergency stop is triggered, ensuring that it does not fall over or collapse uncontrollably. However, the software implementation and validation of the SSE under all operating conditions remains an open research problem.

The transition from traditional brownfield environments toward Industry 4.0 and ultimately Industry 5.0 is characterised by increasing levels of digitalisation, autonomy, and human-machine integration. Figure 4 illustrates this progression by mapping key technological pillars—smart human interfaces, digital connectivity, artificial intelligence, digital factory systems, and robotics—onto different stages of industrial evolution. It highlights how applied factories, dark factories, and humanoid-robot factories represent escalating degrees of automation and system intelligence.

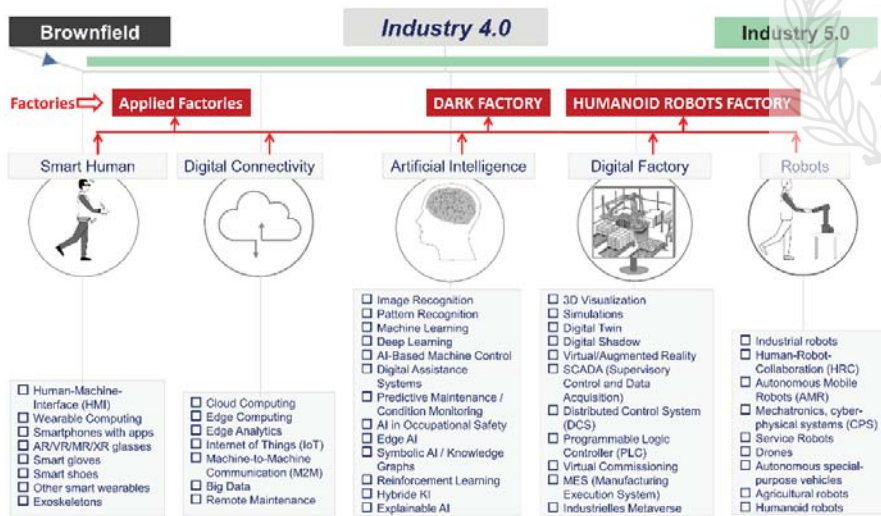


Figure 4. Positioning of the Dark Factory and Humanoid Factory within the context of Industry 4.0 and Industry 5.0

McKinsey's 2024 report "The future of physical AI: How humanoid robots are stepping into the brownfields of manufacturing" reinforces this trajectory. The study argues that humanoid robots are emerging precisely at the intersection shown in the graphic: they enable existing brownfield plants to adopt advanced

automation without requiring full redesigns. According to McKinsey, humanoids act as a bridging technology between Industry 4.0 automation and Industry 5.0 human-centric, adaptive production systems by taking over physically demanding, repetitive, or ergonomically challenging tasks while integrating seamlessly into legacy environments. [7]

Together, the visual model and McKinsey's analysis demonstrate that the convergence of AI, robotics, and digital factory technologies is not only reshaping greenfield innovation but increasingly transforming established brownfield manufacturing into hybrid, flexible, and progressively autonomous production architectures.

4. Methodological Approach

This comparative analysis of two automation approaches is based on a systematic literature review, expert interviews, and a qualitative content analysis of current industry publications. This methodological approach ensures that theoretical concepts and their practical implications are compared transparently and objectively.

In addition to primary academic literature, the analysis incorporated practical secondary sources. This is necessary because humanoid robotics is currently undergoing a rapid phase of industrial testing, the results of which are not always immediately reflected in academic literature.

The evaluation comprises:

- manufacturer information and white papers containing technical specifications and deployment reports from leading robotics companies, including Tesla, Boston Dynamics, Figure, and Agility Robotics;
- regulations and standards, including current safety and interface standards (ISO 10218, ISO/TS 15066 and VDA 5050), as well as EU machinery regulations;
- documentation of pilot projects;
- reports on real-world pilot phases in the automotive and logistics sectors (e.g. BMW and Mercedes-Benz).

Examples: Dark Factory and humanoid pilot projects

Since the 1990s, FANUC has been operating several production lines capable of running fully automatically for up to 30 days without interruption. CNC machines manufacture components, which are transported to the assembly line by autonomous transport systems. There, industrial robots assemble and package new robots. The employees are responsible for planning, programming and maintenance. [4]

Xiaomi's smart factory in Beijing launched a fully automated "dark factory" in 2023. It produces over one million smartphones per year. Production runs around the clock without the need for human presence, shift changes, breaks, or lighting. An AI-based platform controls and optimizes processes in real time, performs automated quality control via image processing, and enables predictive maintenance. [14]

Philips has officially described the factory in Drachten (Netherlands) as one of the "smartest factories in Europe" since 2020. In the highly automated production, in which over 300 robots and autonomous transport systems work together in 24/7 operation, razors and personal care devices are created with minimal human presence. [11]

For the Humanoid Factory perspective, current pilot projects in humanoid robotics – such as Tesla Optimus, Figure 01 (BMW pilot [2]), Apptронik, Apolo (Mercedes-Benz pilot [1] and Agility Robotics "Digit" (Amazon pilot [6]) – were included, as they reflect the current state of technological development and the practical limitations of humanoid systems. These examples served as empirical reference points for the qualitative content analysis.

Recent industrial deployments underline this trend. Sanctuary AI, for example, has released the next generation of its Phoenix general-purpose robot and announced a deployment partnership with Magna International, demonstrating that humanoid and humanoid-adjacent systems are beginning to enter real brownfield manufacturing environments [8].

Tesla has also begun deploying its Optimus Gen-2 humanoid robot in automotive manufacturing environments, focusing on neural-network-based behaviour training and task generalisation. This illustrates how major industrial players are experimenting with AI-driven humanoid systems in real brownfield settings [9].

The collected data is synthesised using a custom-developed criteria matrix. These evaluation criteria are derived directly from the core requirements of Industry 5.0 [3]. The two automation approaches are then compared in a standardised way, based on their technological drivers, safety concepts and organisational implications for the workforce.

5. Comparative Analysis of Automation Systems

The future viability and potential applications of the 'Dark Factory' and the 'Humanoid Factory' are thoroughly assessed through a systematic comparison of the two concepts across four key dimensions: technology, economics, safety and organisation.

5.1 Technological Dimension: Autonomy vs. Flexibility

The technological divergence between the two paths is evident in their inherent control and system paradigms. The Dark Factory embodies the principle of deterministic full automation. The technological infrastructure is based on a rigid interlinking of cyber-physical systems (CPS), in which every machine, every driverless transport system, and every sensor communicates via standardized protocols. System stability is guaranteed by the elimination of unpredictable variables.

While the Dark Factory achieves maximum autonomy with minimal flexibility, the Humanoid Factory positions itself closer to the human performance spectrum in terms of adaptability and the ability to handle variations. The outlined development directions illustrate the current research's endeavor to bridge the technological gap toward highly autonomous yet flexible systems.

Unlike the Dark Factory, which relies on rigid, fully standardised processes, the Humanoid Factory uses flexible robots that mimic human movement. The focus shifts from mechanical infrastructure to software control. Thanks to AI models and modern image processing, these robots can act as universal workers, recognising ambiguous situations and interpreting tasks in real time, while also independently compensating for deviations or tolerances. While the Dark Factory achieves precision through maximum process standardisation, the Humanoid Factory leverages the robots' ability to adapt to unpredictable real-world conditions — much as a human would. That's the developers' plan. The industry is eager to see if it can be implemented as planned, but above all it wants to ensure that security is guaranteed.

5.2 Economic Dimension: Greenfield vs. Brownfield Investments

From a business and production technology perspective, the investment and operating cost structures of “dark factories” and “humanoid factories” differ fundamentally.

Dark Factory (Greenfield Approach)

A fully autonomous Dark Factory requires significant initial investment, as the entire production facility must be designed from the ground up. The infrastructure is tailored precisely to the machines, material flows, and automated processes.

Typical characteristics:

- - New facility or extensive renovation
- - Highly specialised equipment
- - No human workstations
- - Fully standardised processes

The economic benefits only become apparent during ongoing operations, primarily due to:

- Elimination of personnel
- Lower energy requirements (no lighting, minimal heating).
- Reduced occupational safety requirements
- Very high throughput for large quantities.

Conclusion: The high initial costs make this worthwhile only for stable processes and very large production runs.

Humanoid Factory (Brownfield Approach)

This approach enables the gradual automation of existing production facilities without the need for structural modifications. A humanoid robot is acquired and used as a mobile work tool wherever staff numbers are low or processes vary.

Advantages:

- Significantly lower initial investment
- No need to modify halls, workstations or tools
- Quick integration into existing processes
- Flexible deployment across various workstations
- Ideal for high product variety and smaller batch sizes

The economic benefits arise from:

- A flexible response to changing orders
- Relief during skilled labour shortages
- Reduced downtime
- Use of existing infrastructure

Conclusion: Lower initial costs make it particularly worthwhile for high-variety production and in situations of labour shortage.



5.3 Safety and Regulatory Aspects

From a safety perspective, this is one of the biggest challenges currently facing the deployment of humanoid robots. In a dark factory, the safety architecture is clearly defined and spatially separated. Since humans are not permitted in the production area during normal operation, safety fences, light curtains and interlocks can provide full protection. If someone enters the area, the system stops immediately. This consistent physical separation of humans and machines largely eliminates the potential for danger.

However, this principle does not apply in a humanoid factory. Although production operations here are also human-free, the humanoid robots move freely in an environment originally designed for human workers. Therefore, spatial separation through safety zones is not practical. Instead, safety must be ensured intrinsically through reliable collision avoidance, limitation of forces and speeds, safe sensor and actuator technology, and functional, AI-supported motion planning. This is where the regulatory conflict arises. Current standards, such as ISO 10218, ISO 13849 and IEC 62061, as well as the new EU Machinery Directive (from 20 January 2027 EU Machinery Regulation), stipulate that the movements of robots must be deterministic, predictable and verifiable. However, humanoid robots whose AI can react to unstructured situations only meet these requirements to a limited extent at present. Since there are currently no standardised testing and certification frameworks for autonomous, AI-controlled motion sequences, the widespread industrial use of humanoid robots in open production environments will be heavily restricted by regulations in the short and medium term.

5.4 Organizational Dimensions in the Context of Industry 5.0

The Dark Factory embodies the principles of Industry 4.0, including maximum standardisation, full digitisation, and complete connectivity.

A small team of highly qualified specialists is responsible for maintenance, process monitoring, and plant optimisation outside the production hall.

In contrast, the Humanoid Factory is guided by the principles of Industry 5.0: resilience, adaptability and human-centred system design. Although operational production can take place without a human presence, humans remain closely integrated into the organisation as supervisors, teleoperators, process designers, and problem solvers. Humanoid robots perform monotonous, ergonomically demanding, or safety-critical tasks, while humans flexibly intervene in situations involving variability, disruptions, or complex decisions.

This division of roles increases the systemic resilience of the production network. When faced with market changes, supply chain disruptions or highly varied

customer orders, the Humanoid Factory can react more quickly, as adjustments primarily involve software, and human expertise is always available.

5.5 Synthesis: The Criteria Matrix

The following matrix compares the 'Dark Factory' and 'Humanoid Factory' automation approaches based on technical, organisational, and safety criteria. It can be used as a strategic guide when designing future factory architectures.

The 'Dark Factory' approach is particularly well-suited to high-volume, standardised production environments. Advantages include maximum process efficiency, low variable costs after commissioning, and a technologically mature foundation. However, it offers less flexibility with regard to product changes and high-variety manufacturing.

The 'Humanoid Factory' approach has high potential due to its compatibility with existing infrastructure and its ability to adapt to software changes. Currently, however, these advantages are offset by the approach's low technological maturity, high investment costs, and unresolved safety and infrastructure issues. Table 2 is the first to compare the two paradigms across twelve dimensions, incorporating the safety perspective. This perspective has largely been overlooked in previous studies.

Terms:

Cyber-Physical Systems (CPS): Real-time networked systems integrating machines, sensors and digital control. They form the basis of Industry 4.0 automation.

Intrinsic safety of humanoid robots: A safety principle whereby the robot autonomously establishes safe states through sensors, AI-based motion planning and control-related limitations. This principle is central, yet it has not yet been fully standardised.

Enablers for Industry 5.0 Resilience: Humanoid robots increase the adaptability of industrial systems, enabling flexible responses to changes in the market and supply chain.

OEE (Overall Equipment Effectiveness) describes the actual effectiveness of a production unit. It consists of three factors: availability, performance and quality. OEE is the key metric for objectively comparing the efficiency of production systems.

Large Behaviour Models (LBMs) are AI models that can process language and learn to perform complex sequences of actions. They connect: LBMs enable humanoid robots to understand and adapt to their environment, performing tasks rather than merely executing pre-programmed movements.

The comparative analysis of the two automation pathways is based on a systematic literature review and qualitative content analysis of recent industry publications. This approach ensures that the theoretical concepts and their practical implications are compared transparently and objectively.

Table 2: Dark Factory vs. Humanoid Factory comparison matrix

CRITERIA	DARK FACTORY	HUMANOID FACTORY
Primary goal	Maximum process efficiency & continuity	Maximum adaptability & flexibility
Human presence	Low (Monitoring, Service & Maintenance)	Low (Teleoperation, Monitoring, Service, Maintenance outside of Operations)
Primary Automation	Industrial robots, AGVs, CNC, MES	Humanoid robots + LLM cognition
Flexibility	Low to medium (task-specific)	High (adaptive, trainable)
Product changeover costs	High (mechanical conversion)	Low-medium (software re-training)
Acquisition costs	Very high (infrastructure)	High (robot hardware, software licenses)
Operating costs	Low (after amortization)	Resources (energy, maintenance, updates)
Technological maturity	Highly established market	Low to medium (from 2030 and later)
Main focus of operations	Mass production, chemicals, pharmaceuticals, automotive	Small series production, logistics, variant manufacturing
Operating hours/day	24/7 (continuous)	2–8 hours (currently, target: 16–20 hours with spare batteries)
OEE (Overall Effectiveness)	85–95%	Research prototype, trials in production
Conversion compatibility	Requires new construction / renovation	Compatible with existing infrastructure (development is not yet foreseeable)
Security concept	Spatial separation (protective fences/light curtains)	Intrinsic safety (sensors/AI control)
Safety standard	ISO 10218-1/- 2, ISO 13849/ IEC 62061, ISO 12100	ISO/CD 25785-1/-2 (both in development)
Technology drivers	Cyber-physical systems, IoT, deterministic sensors	AI, Large Behavior Models, Computer Vision
Technology classification	Consistent implementation of Industry 4.0	Enablers for the resilience of Industry 5.0

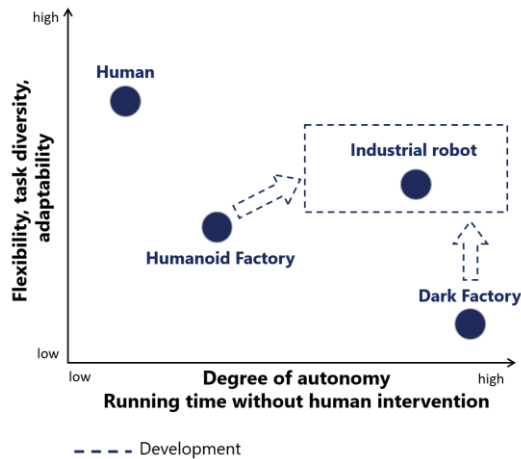


Figure 5. Positioning of Dark and Humanoid Factories

Figure 5 shows a two-dimensional diagram illustrating the positioning of humans, industrial automation systems, Dark Factory concepts, and humanoid robot systems along two central dimensions. The horizontal axis describes the degree of autonomy or the possible operating time without human intervention. The vertical axis represents flexibility, task diversity, and adaptability.

The upper left area represents the human, characterized by high flexibility but low autonomy. The lower right area represents the Dark Factory, which exhibits a very high degree of autonomy but low task flexibility. Between these two extremes are classic industrial robots, which possess high process autonomy but limited adaptability.

The Humanoid Factory is depicted in the middle to upper part of the diagram and represents a system that strives for both greater flexibility and increasing autonomy. The depicted development paths illustrate two different technological directions:

- the deterministic automation of industrial robots towards the Dark Factory and
- the adaptive automation of humanoid systems, which in the long term should enable a greater variety of tasks and longer autonomous operating times.

The diagram thus visualizes the two fundamental automation paradigms: maximum standardization (Dark Factory) versus maximum adaptivity (Humanoid Factory).

This positioning indicates that humanoid-robot factories function as a bridging technology, enabling brownfield plants to evolve toward Industry 5.0 without requiring disruptive infrastructure redesigns.

6. Discussion and Future Outlook

The development directions shown in Figure 5 confirm this assessment and illustrate the divergence between deterministic and adaptive automation. The comparative analysis demonstrates that the "Dark Factory" and the "Humanoid Factory" are not competing, but rather complementary development directions in industrial automation. This chapter discusses the implications for future factory architectures and outlines the path to a hybrid production model. The development directions shown in Figure X confirm this assessment and illustrate the divergence between deterministic and adaptive automation.

The results of the criteria matrix suggest that for the majority of industrial companies, focusing exclusively on only one of the two paths is either economically unviable in the short and medium term (Dark Factory in a volatile market environment) or technologically unfeasible (humanoid factory due to its low level of maturity). The evidence instead points to the emergence of hybrid production models.

In such a hybrid factory architecture, highly standardized core production operates as a "Dark Factory zone" (Lights-out). Humanoid robots function as a flexible, complementary technology at the interfaces. They close automation gaps in areas that are inaccessible or unergonomic for conventional machines – for example, in flexible material supply, quality control of highly variant components, or adaptive machine loading in brownfield environments.

To enable the gradual integration of humanoid robotics into existing industrial structures, this work identifies three key research areas:

- Hardware reliability: Classic industrial robots achieve tens of thousands of maintenance-free operating hours, while bipedal humanoid systems in pilot phases still exhibit short uptimes. Research focuses on robust, energy-efficient actuators.
- Standardization of safety standards: A regulatory vacuum exists. Existing standards for human-robot collaboration (e.g., ISO/TS 15066) are not transferable to mobile, human-sized humanoids with AI-based motion planning. New certification criteria are needed for the functional safety of Large Behavior Models (LBMs) and other integrated AI models.
- Background infrastructure (fleet management): While established interfaces such as VDA 5050 exist for AGVs/AMRs, a standardized orchestration software that enables seamless integration into existing IT systems is lacking for humanoid general-purpose robots.

One limitation is that the evaluation of the Humanoid Factory is primarily based on current model projects, manufacturer specifications, and theoretical concepts. Due to rapid technological development, empirical long-term data on actual

operating costs and life cycle parameters of large-scale humanoid systems operating in three shifts are still lacking.

7. Conclusion

The analysis shows that the Dark Factory and the Humanoid Factory represent two complementary, yet fundamentally different, automation paradigms. The Dark Factory embodies the efficiency maximum of deterministic Industry 4.0 automation, while the Humanoid Factory, as an adaptive Industry 5.0 concept, focuses on flexibility, resilience, and infrastructure compatibility. Both approaches, when implemented in isolation, encounter functional limitations: the Dark Factory due to a lack of adaptability, and the Humanoid Factory due to technological maturity and a lack of standardization. The results therefore suggest that future factory architectures will be designed not monolithically, but as hybrids. In such systems, the Dark Factory zone handles highly standardized core production, while humanoid robots, as flexible complements, fill automation gaps. As the field is developing quickly, the findings represent the current state of knowledge and may require revision as new standards and industrial deployments emerge. This creates a production model that combines efficiency and adaptability and structurally enables the transition from Industry 4.0 to Industry 5.0.

References

- [1] Apptronik. (2024). Apptronik and Mercedes-Benz enter commercial agreement to pilot Apollo humanoid robot in manufacturing facilities. Apptronik News. Online https://apptronik.com/news-collection/apptronik-and-mercedes-benz-enter-commercial-agreement?utm_source=copilot.com, accessed on 02.06.2025
- [2] BMW Group. (2026, 4. März). Erfolgreicher Pilotversuch im BMW Group Werk Spartanburg: Humanoide Roboter Figure 02 unterstützen Serienfertigung im Karosseriebau. BMW PressClub.
- [3] Europäische Kommission. (2021). Industrie 5.0: Für eine nachhaltige, menschenzentrierte und widerstandsfähige europäische Industrie. Amt für Veröffentlichungen der Europäischen Union.
- [4] Industrial Automation. (2026). FANUC Corporation. FANUC: The Benchmark for Lights-Out Manufacturing and Industrial Automation. Online: https://www.industrialautomationindia.in/articles/fanuc-lights-out-manufacturing-benchmark?utm_source=copilot.com, accessed on 03.06.2026
- [5] Fraunhofer-Institut für Produktionstechnik und Automatisierung (IPA). (2024). Der schmale Grat zur Dunkelfabrik: Potenziale und Grenzen vollautomatisierter Produktionssysteme. Fraunhofer-Eigenverlag.

- [6] Agility Robotics, (2023). Apptronik and Mercedes-Benz Enter Commercial Agreement. *Apptronik Press Release*. Online <https://www.agilityrobotics.com/content/agility-robotics-broadens-relationship-with-amazon>, accessed on 04.06.2026
- [7] McKinsey & Company. (2024). The future of physical AI: How humanoid robots are stepping into the brownfields of manufacturing. *McKinsey Operations Insights*.
- [8] Sanctuary AI. (2024). Sanctuary AI releases next generation of Phoenix general purpose robot and partnership deployment with Magna International. Robotics 24/7.
- [9] Tesla, Inc. (2025). Tesla Optimus: Gen 2 deployment and neural network behavior training in automotive factories. Tesla AI & Robotics Division.
- [10] Ulrich Baldauf, (2026). Humanoid Robot Safety Standards 2026: Best Compliance Guide. Online: <https://theresarobotforthat.com/blog/humanoid-robot-safety-standards-2026/> accessed on 25.05.2025
- [11] Philips, (2022). Werken bij Philips Drachten: één van de slimste fabrieken van Europa. Online <https://www.philips.nl/a-w/about/news/archive/standard/about/news/articles/2022/20220916-werken-bij-philips-drachten-een-van-de-slimste-fabrieken-van-europa.html>, accessed on 22.05.2026
- [12] Pao, J. (2025). ASTM Calls for Urgent Safety Standards for Humanoid Robots. In: Tech Journal UK, ASTM International. Online: <https://www.techjournal.uk/p/astm-calls-for-urgent-safety-standards>, accessed on 02.06.2026
- [13] Industriezeitschrift.de, (2025). Sicherheitsaspekte bei humanoiden Robotern. Online: <https://industriezeitschrift.de/robotik/humanoide-roboter/sicherheitsaspekte>, accessed on 01.06.2026
- [14] ertugrulturgay.com, (2025). The Factories of the Future Shine in the Dark. online <https://ertugrulturgay.com/the-factories-of-the-future-shine-in-the-dark/>, accessed on 03.06.2026