

Article

A Method to Evaluate the Maturity Level of Robotization of Production Processes in the Context of Digital Transformation—Polish Case Study

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Abstract: This paper puts forth a systematic approach to evaluating the maturity level of the robotization of production processes in the context of digital transformation for manufacturing companies. The method was developed to address the absence of a sector-specific framework for assessing robotization maturity growth, in line with the Industry 5.0 guidelines (incorporating sustainability, the circular economy, and human-centeredness). The survey covers six core areas for manufacturing companies: the automation and robotization of production processes, digitization of warehouse processes, flexibility and intralogistics, and end-to-end integration of key data management processes. The study aimed to advance digitalization through improved robotization maturity. The study surveyed 200 small and medium-sized businesses operating in Poland from 2022 to 2024. The study presents a method to assess enterprise operational maturity, covering current and planned levels and development plans for the next three years.

Keywords: Industry 4.0/5.0; digitization; robotization; digital transformation



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1. Introduction

Today's robotization of technological processes encompasses new areas beyond classic robot applications [1–7]. Various types of robotic implementations have been utilized for many years (e.g., machine and process line operation, pick-and-place, material handling, packaging and palletizing, assembly and disassembly, welding and soldering, batching, gluing, painting, processing, grinding, milling, cutting, quality control, testing, die casting, etc.). However, these classic implementations of robots still need to be challenged.

Robotization can be adapted to meet the requirements of Industry 5.0, emphasizing waste minimization and energy conservation [8–11]. Industry 5.0 builds on the Industry 4.0 [12–16] approach and expands its scope to include a regenerative purpose and focus. The goal is to transform industrial production to benefit people, the planet, and well-being rather than solely to extract value. The robotization of technological processes allows for increased production flexibility and resilience in the face of a shortage of skilled workers. The criteria mentioned above remain crucial for attaining the intended level of productivity. Industrial robots have a pivotal role in promoting sustainable development. They help increase resource productivity, reduce hazardous emissions, such as greenhouse gases and other pollutants, and improve production quality, which results in less waste. Additionally, they enhance workers' functional safety. Collaborative robots have revolutionized production facilities by replacing or working with employees [17–20].

Figure 1 illustrates the key drivers [21–25] for Industry 5.0's growth.

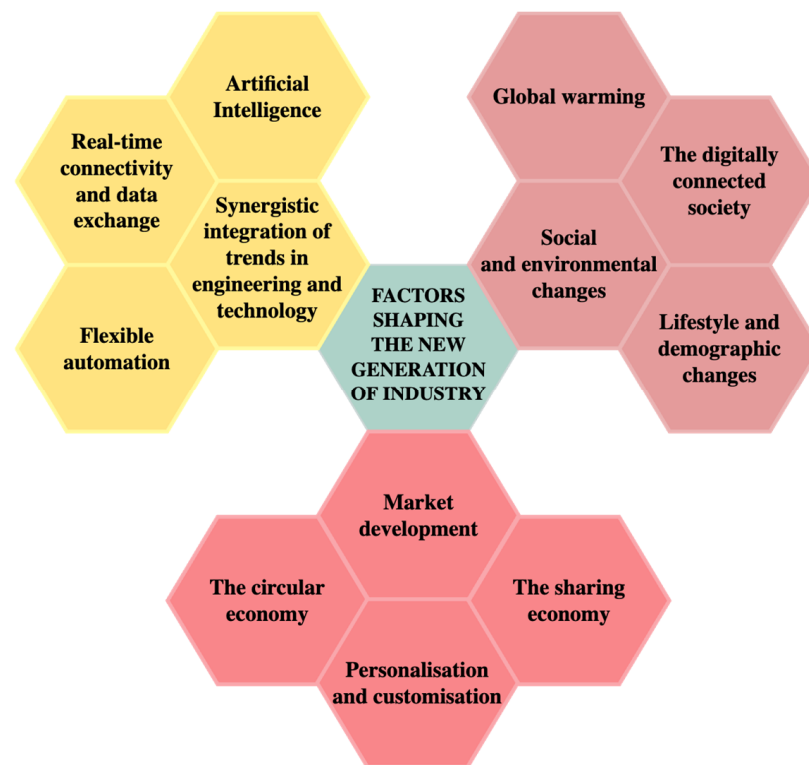


Figure 1. Key growth drivers for Industry 5.0 [21–25].

Table 1 shows the notable distinctions between the objectives of Industry 4.0 and Industry 5.0. These disparities are due to the adoption of new assumptions [26–29], which serve as the foundation for a socially responsible approach to the robotization of production processes and the changes that come with companies’ digital transformation.

Table 1. A comparison of the fundamental areas of Industry 4.0 versus Industry 5.0 [26–29].

Industry 4.0	Industry 5.0
• Focus on increased efficiency—thanks to digital connectivity and artificial intelligence, • Technology centered around the emergence of Cyber–Physical Systems, • Adapting business models to be optimized within existing capital market dynamics and economic models (i.e., oriented towards cost minimization, profit maximization, production, and operational efficiency), • Lack of focus on the design dimensions and actions needed for systemic transformation, • A need for decoupling of resource and material use from negative environmental, climate, and social impacts.	• Providing a framework for industry combining competitiveness and sustainability, enabling industry to realize its full potential as one of the pillars of transformation, • Highlighting the impact of alternative (technology) management approaches on sustainability and resilience, • Empowering employees using digital devices (advocating a human-centered approach to technology), • Building transition paths towards environmentally sustainable technology applications, • Extending corporate responsibility to entire value chains, • The introduction of indicators (for each industrial ecosystem) mapping the progress made towards prosperity, resilience, and overall sustainability.

Robotization combined with a consciously carried-out automation process meets the needs of Industry 5.0’s new challenges, as indicated by the development trends illustrated in Figure 2.



Figure 2. Main development trends in robotization of production processes.

There is a growing interest in collaborative robots in process automation, according to recent trends [30]. This state is because flexible safety systems can replace inflexible ones with easy programming and a wide range of applications at a lower price point. The need to employ or outsource the services of skilled programmers can be significantly reduced by using low-code and no-code programming methods. It is essential to consider the requirements for End-of-Arm Tooling [30], such as tooling performance (ease of change, flexibility, adaptability, programming, and safety design) to minimize downtime between processes. Noncompliance with EoAT requirements could sometimes alter the robot–worker interaction, transitioning from collaboration to cooperation or coexistence.

Artificial intelligence and machine learning are growing, evident in their functionality. These techniques aid in diagnosing and predicting operating conditions, optimizing energy usage, and governing the course of action. Robots are now equipped with intelligent sensors [31,32]. This provides full operation autonomy and integrates quality control for products and the process.

The offline programming method using Digital Twins is changing how robots are programmed (the technology is utilized for diagnosing and simulating the robot’s performance within the production environment) [33].

One significant change is the robots’ expanded functionality and application in previously unexplored areas. Mobile robots [32,33], including autonomous vehicles used in intralogistics, play a critical role and are considered essential for various applications. To meet the requirements of security, flexibility, and reliability, it is necessary to use advanced security systems, fast and reliable wireless networks, localization methods, and conflict arbitration mechanisms. Mobile robots are used to develop internal traceability systems in warehouses and production areas [34]. Robotic workstations and individual robots are now often connected to data clouds to optimize processes and evaluate KPIs in industrial automation [32–34].

Attitudes towards the necessity of robots have recently undergone a shift. Robot-as-a-Service (RaaS) [35] has emerged, eliminating the need to purchase a robot and necessary tooling. RaaS offers classic advantages, such as lower initial investment costs, flexibility, and scalability to meet current needs. Additionally, it allows outsourcing maintenance and support services and accessibility to the latest market technologies. This model provides cost predictability, remote monitoring and management, rapid integration into existing production systems, and customization of provided market solutions. RaaS has lowered

the barrier to entry for small and medium-sized enterprises to implement industrial process robotization solutions.

The fields of robotics and automation have been complementary for many years. However, these areas are gaining more importance in an era of widespread reshoring [36–38]. However, it is crucial to identify the specific application's needs and select the appropriate robot accordingly.

The primary trend in the market is the digitalization of production processes, which neglects the aspects of robotics and automation [39–49]. For entrepreneurs, automation and robotization are fundamental factors in building the foundations for the development of digitally managed production [50–54]. The level of robotization maturity, entrepreneurs' awareness of robot selection, necessary tooling, and infrastructure adaptation need to be evaluated.

The author has developed a method to evaluate the maturity level of manufacturing companies in terms of robotization, considering the digital transformation process and environmental factors. The basic rationale for the method's development is the lack of knowledge about the implementation of robotization in terms of needs, expected functionalities, and the scalability and freely expandable nature of industrial systems.

2. A Method for Assessing the Maturity Level of Key Areas in Manufacturing Companies

2.1. The Main Obstacles to the Robotization of Production Processes

Robotizing production is complex and requires careful planning, purchasing, and integration. Fundamental issues may include:

- Analysis of the factors determining the feasibility of implementing a robot;
- Selection of a robot for a specific application—it is essential to consider various factors such as kinematic structure, load capacity, degrees of freedom, reach, mounting type, speed, motion range of joints, motion repeatability, IP class, operating temperature range, built-in/optional communication ports and IO interfaces, programming method and environment, tooling, and installation requirements;
- Estimation of implementation costs, including the purchase and maintenance expenses, in comparison to the costs of other solutions available in the market;
- Selection of sensors and additional instrumentation (grippers with tactile sensors, accelerometers, 3D vision systems, force and torque sensors, glue or paint guns, welding guns, etc.);
- The need to meet requirements for the operating environment in which humans and robots interact and the safety measures that need to be considered during operation;
- Integration of IIoT collaborative robots, including connectivity technologies such as Ethernet, Wi-Fi, Bluetooth, GSM systems, 5G, and software integration;
- The need to provide necessary additional instrumentation (e.g., utilities, gas extractors, etc.) and adaptation of infrastructure;
- Training of employees; hiring or outsourcing qualified staff.

Based on initial surveys, the most frequently used criteria (C1–C5) by entrepreneurs have been identified in the form of:

- C1—Relocating time-consuming processes to robotic workstations while transferring operators to higher-value tasks;
- C2—Elimination of routine quality problems (frequent need for scrap or rework) and areas of inconsistent quality;
- C3—Elimination of the manipulation of heavy tools or parts, workplaces, or locations with potential for dangerous accidents;
- C4—Handling monotonous and rule-based operations (e.g., sorting, simple logic);
- C5—Moving workers away from hazardous areas (exposition to gases, dust, or by-products of the production process) and eliminating manual activities (with repetitive movements and ergonomic problems and those requiring prolonged, intensive concentration or constant change of attention).

The criteria that have been indicated include issues related to technology, ergonomics, and process reorganization. However, key requirements such as energy savings, reduced adverse environmental impacts [55,56], and continuous improvement, including the possibility of integrating robots into digitized complex enterprise management systems [57–63], must also be included.

2.2. Aims, Objectives, and Structure of the Proposed Method

The author developed a method that uses a five-point scale to evaluate the maturity of a manufacturing company's operations in six key areas, which include:

- Automation of production processes—a key area of development that determines the possibility of the digitalization of production, as well as the integration of production and management processes;
- Robotization of production processes—a key area of development for increasing the quality, reproducibility, productivity, and autonomy of manufacturing workstations, as well as the redeployment of employees to higher-value tasks;
- Digitization of intralogistics warehouse processes—a key area of development determining the ability to efficiently manage and optimize inventory levels, including inputs, finished products, equipment, and tools;
- Flexibility of production systems—a key area of development for achieving agility relies on improving internal processes such as dynamic path routing and increasing machine Overall Equipment Effectiveness ratios, as well as external processes such as responding quickly to market changes;
- Intralogistics of production processes (inter-station and inter-department transport)—a key development area for achieving agile automation in material and product flow streams;
- Integration of management, production, quality control, intralogistics, and warehousing systems—a key area of development for achieving Single Source of Truth data exchange status between all systems for managing and controlling company processes.

Key areas of the maturity level assessment method for manufacturing companies are illustrated in Figure 3.

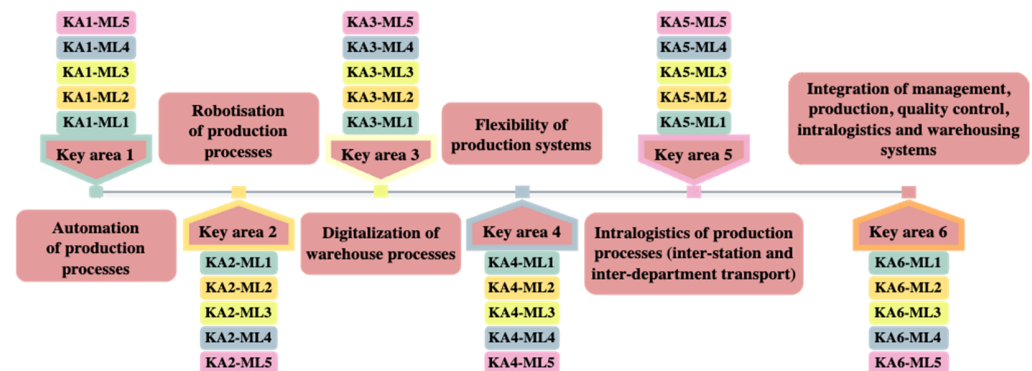


Figure 3. Key areas of the maturity level assessment method: ML1–ML5—maturity levels in a specific key area.

Figure 4 shows a matrix of the manufacturing company's key areas and maturity levels. The rows correspond to the current and target maturity levels, while the columns represent the individual key areas.



Figure 4. Matrix of key areas and maturity levels of the manufacturing company.

Guidelines and recommendations have been defined for each maturity level of all areas to identify current and target states, which are specified as follows:

- Current state—a set of characteristics defining the minimum requirements of a selected key area, divided into categories representing the characteristics of a specific maturity level;
- Advantages—three independent sub-areas (machinery, infrastructure, and equipment; human resources; processes) defining strengths in each maturity level of a specific key area;
- Disadvantages—three independent sub-areas (machinery, infrastructure, and equipment; human resources; processes) defining weaknesses in each maturity level of a specific key area;
- Growth opportunities—a set of necessary directions to identify technological deficiencies (machinery sub-area), skills gaps (human resources sub-area), and process optimization (processes sub-area);

- Recommendations—recommendations including the implementation of measures to achieve a higher level of maturity.

The method involves selecting a specific key area's current and target states. Defining the initial and target states requires meeting the requirements of lower maturity levels. The key areas are closely interlinked and intersect at the development planning and implementation stages. It is possible to evaluate a company's level of maturity in a specific area that is considered a priority. However, implementing the recommendations suggested to reach the target state will always increase the overall maturity level.

The maturity level assessment is conducted separately in the specified key areas. The area chosen for analysis depends on personal preferences and current development needs. The first step is to assess the compatibility of the solutions used with the elements in the current state scope to identify the initial level of maturity.

As shown in Table 2, each of the five maturity levels within a specific key area is rated on a five-point implementation scale.

Table 2. The scale of implementation of the defined maturity levels.

Implementation Scale	Identifier	Characteristics
Level 1	Chaotic	The indicated solutions are either not being applied, or they are being implemented without proper definition, planning, structure, and management before and during implementation; this includes the level of service, training, and utilization of the potential of machinery and equipment.
Level 2	Defined	The activity areas have been accurately defined for applying key solutions, and conscious implementation has been carried out in selected areas; however, a long-term plan for integration and further development has not been established; meeting development needs is currently performed on an ad hoc basis.
Level 3	Planned	A multi-stage implementation process was developed; for example, the implementation of the proposed solutions was planned in the short term; an implementation timetable and milestones were developed, and training and staff deployment processes were planned.
Level 4	Managed	The solutions identified are implemented, and the ability to manage implementation and use is achieved professionally; procedures are in place to identify and implement changes, address needs, and assess their validity.
Level 5	Optimized	The level of optimization has been achieved in the solutions used, supported by mature change management processes in the focal area.

The scale has been designed to indicate increasing levels of advancement. The highest level of advancement allows for optimizing a specific key area, leading to increased maturity.

The author defined the scale in terms of criteria for ownership, management, and the utilization of specific technological and IT solutions. This allows the evaluation to encompass the identified solutions' organizational and planning methods, competencies, knowledge, and utilization level.

Figure 5 shows the algorithm for evaluating the defined maturity levels across key areas. Reaching the fifth level of implementation makes moving to the next level of maturity achievable.

The author's fundamental premise is that acquiring and utilizing modern technology, advanced machinery, and equipment requires proper management to ensure optimization and the development of the issues identified in the respective key areas. Continuous improvement solutions should be implemented in each case.

The following section delves into the characteristics of the primary area addressed in the article.

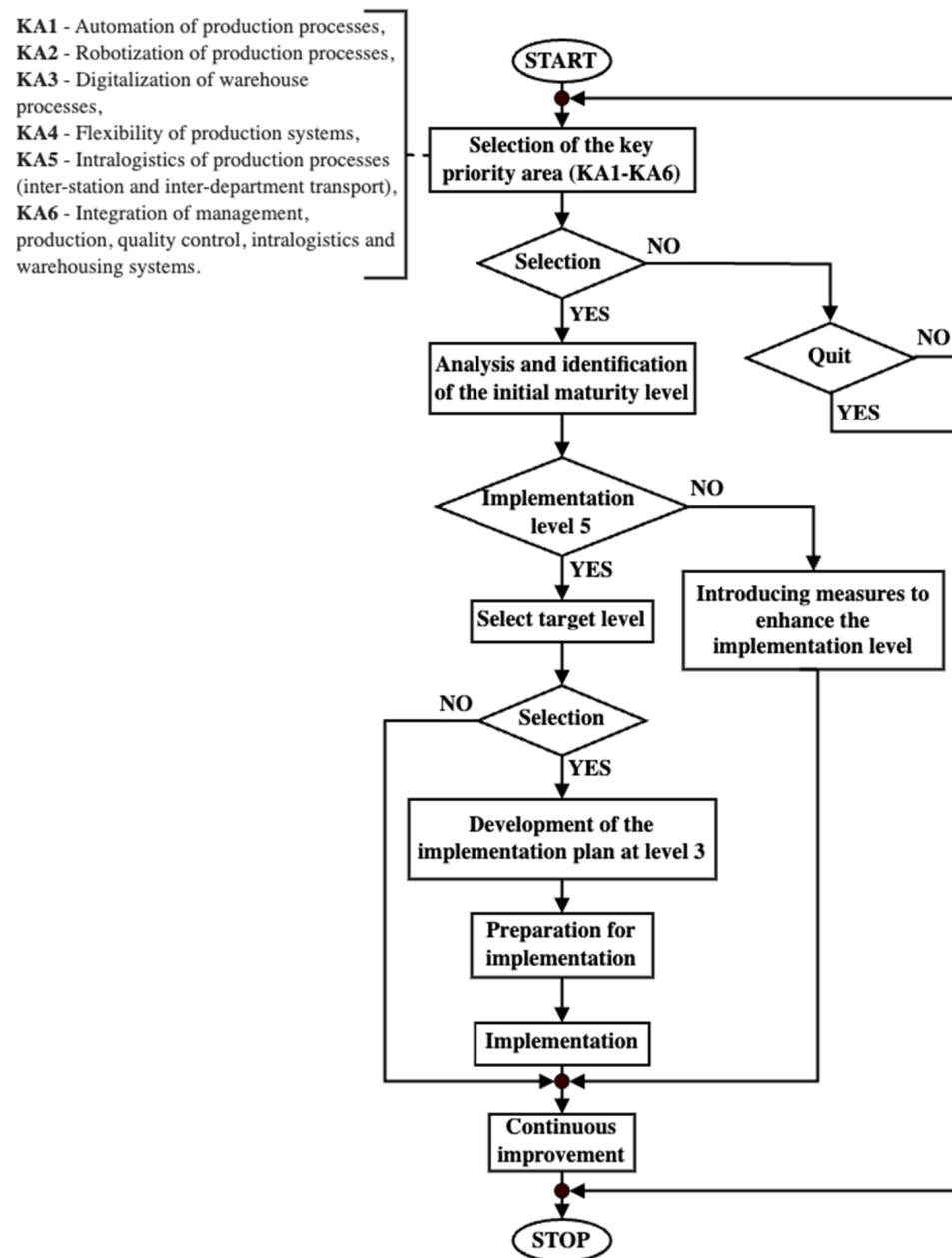


Figure 5. Algorithm for evaluating the defined maturity levels across key areas.

2.3. Characteristics of the Key Area—Robotization of Production Processes

The stages of robotization in production processes are classified into maturity levels, ranging from ML1 to ML5 (as shown in Figure 6). These levels represent increasing degrees of advancement while considering the general trends and assumptions regarding the modern trends of robotization and the concept of the Factory of the Future.

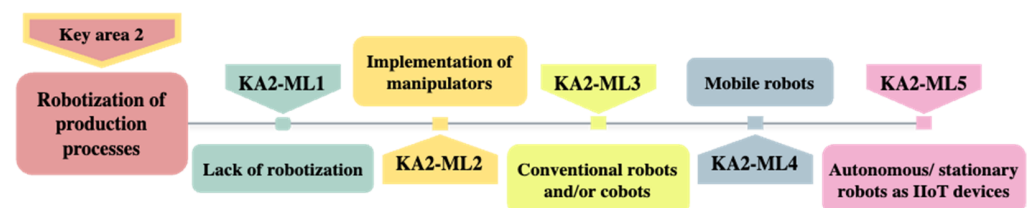


Figure 6. Maturity levels of robotization in production processes.

Figure 7 presents the essential aspects related to the robotization of manufacturing operations. Criteria KF1–KF6 belong to the simple criterion, while criterion KF7 belongs to the composite group. These parameters cover the basic requirements for implementing a new robot solution or modifying an existing one.

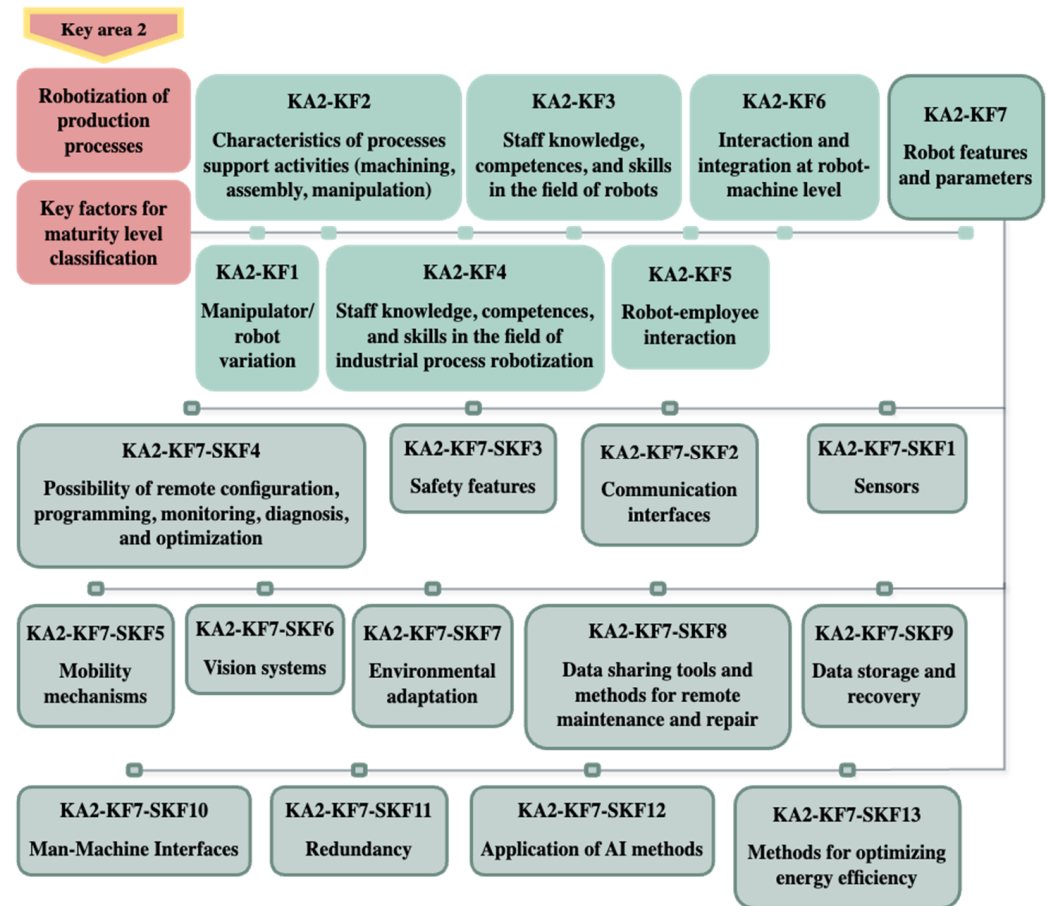


Figure 7. Key factors that determine the maturity level of the robotization of production processes.

Tables 3–7 present the assumptions used to evaluate the maturity of the robotization of production processes. The levels were referred to as the lowest to the highest level of robotization sophistication.

Table 3. The first maturity level of process robotization (KA2-ML1)—lack of robotization.

Level Characteristic	Description and Recommendations
Current state	Lack of implementation of industrial robots: - Manipulator/robot variation—N/A, - Characteristics of processes' support activities (machining, assembly, manipulation)—manual work or assisted processes using mechanical equipment (without external drives), - Staff knowledge, competences, and skills in the field of robots—lack of knowledge, - Staff knowledge, competences, and skills in the field of industrial process robotization—lack of knowledge, - Robot-employee interaction—N/A, - Interaction and integration at robot-machine level—N/A, - Manipulator features and parameters: Sensors; communication interfaces; safety features; possibility of remote configuration, programming, monitoring, diagnosis, and optimization; mobility mechanisms; vision systems; environmental adaptation; data-sharing tools and methods for remote maintenance and repair; data storage and recovery; Man-Machine Interfaces; redundancy; application of AI methods; methods for optimizing energy efficiency—N/A.

Table 3. Cont.

Level Characteristic	Description and Recommendations
Advantages	Machinery, infrastructure, and equipment: • Lack of need to invest in programmers, controllers and control systems, power systems and actuators, communication networks and interfaces, end effectors, sensors, software, consumables, spare parts, and tooling for manipulators and robots, Human resources: • Lack of need to employ staff (or outsource) in programming, maintenance management, and robot repairs, • Lack of requirements for specialized training and technical knowledge in robotization and robotic technology, • Preservation of occupational positions with required upgrading of professional skills, Processes: • Flexibility to adapt processes and staff to current market requirements and production plans (limited by the available machinery—its functionality and efficiency), • Operator-based tasks (manual loading, unloading, possible machining, assembly, and handling of workpieces), • Minimization of the technology dependence (e.g., system failures, technological unemployment), • Minimization of the environmental impact (energy consumption, technological waste from robot and manipulator-aided processes).
Disadvantages	Machinery, infrastructure, and equipment: • Reduction in production volumes (Job Shop Production, Single-Piece Flow, Custom Production), • Flexibility and efficiency of processes depending on the skills and competence of employees and parameters of the objects to be handled or processed (weight, overall dimensions), • Possible reduction in OEE of machines (lack of process balancing, high time value of preparation and finishing work, increased time—handling, mounting, dismounting). Human resources: • Processes dependent on the experience, competencies, and decisions of employees (sensitivity to turnover, absenteeism, skills, well-being, etc.), • Reduced efficiency and increased likelihood of process errors (waste, corrections), • The need to maintain high labor standards and develop incentives for staff retention, • Greater likelihood of injuries and accidents, Processes: • Increased productivity possible through hiring new staff or multi-shift working, • Dimension restrictions, the mass of the workpieces to be handled, and other parameters (efficiency, repeatability).
Growth opportunities	Machinery, infrastructure, and equipment: • Execution of a technology audit (criteria: robot–machine integration, process feasibility, expected performance, utilization rate), • Analysis (or simulation) to justify the implementation of manipulators or robots in the selected production area. Human resources: • Analysis of workplaces in terms of their potential for mechanization or robotization (criteria: repetitiveness and monotony of tasks, current and expected performance, complexity of functions, robot/manipulator–human collaboration, adaptability and potential of workers, adverse health effects, ROI). Processes: • Analysis of production, assembly, storage, and logistics processes.
Development recommendations	• Understanding of the characteristics of manipulators (types, applications, required instrumentation, installation, and commissioning conditions), • Identification of needs, opportunities, and risks for the specific area of robotization under consideration, • Preparing staff for the implementation of the manipulator (analysis of needs and acceptance of change), • ROI analysis and securing funds for the implementation of the manipulator, • Planning all the measures necessary for implementation.

Table 4. The second maturity level of process robotization (KA2-ML2)—implementation of manipulators.

Level Characteristic	Description and Recommendations
Current state	Support for loading, unloading, handling, or manipulation with mechanical units: - Manipulator variation—drive: manual pneumatic hydraulic, electric; mounting: free-standing, on a pole, suspended, on a hanging rail; type of control: manual, positional, sequential, programmed, - Characteristics of processes' support activities (machining, assembly, manipulation)—rigid automation with simple manipulator, - Staff knowledge, competences, and skills in the field of robots—basic knowledge of varieties, applications, operating parameters, and drives, - Staff knowledge, competences, and skills in the field of industrial process robotization—ability to define the area and activities to be assisted by the manipulator, - Robot–employee interaction—fenced manipulators (separating workspaces between manipulator and worker) or coexistence (separate tasks and workspace), - Interaction and integration at robot–machine level—external control (machine controller or PLC), manipulator controller, exchange of digital or analog signals, sequential operation (e.g., pneumatic sequential drive), primarily operating a Single Flexible Machine or an individual automated workstation. - Robot features and parameters: - Sensors—limit switches (mechanical, electrical, reed switches, laser, inductive, capacitive), possible use of encoders, - Communication interfaces—mostly direct connection of actuators and sensors to I/O, industrial serial, and FieldBus-type interfaces, - Safety features—training, procedures, guidelines (for protection against environmental and mechanical hazards, improving general security awareness, minimizing the potential risk of repetitive injuries), fences, - Possibility of remote configuration, programming, monitoring, diagnosis, and optimization—usually N/A (access to the status of sensors from the local controller), - Mobility mechanisms; vision systems, environmental adaptation; data-sharing tools and methods for remote maintenance and repair; data storage and recovery—N/A, - Man–Machine Interfaces—machine control panels or HMIs, - Redundancy; application of AI methods—N/A, - Methods for optimizing energy efficiency—lack of functionality for optimizing energy consumption.
Advantages	Machinery, infrastructure, and equipment: - Support for handling processes, operation of machines and workstations (picking, transfer, reorientation, fixing/unmounting), - Acceptable positioning accuracy, increase in productivity and safety, standardization of process quality, increase in OEE, - Simplicity of construction, repair, and integration (at the lowest possible cost), - Ease of modification and upgrades thanks to modular design. Human resources: - Improved ergonomics while relieving the workload of employees, - Increase productivity, comfort, and quality of work, - Reduction in accidents and injuries, increased worker safety (especially when handling heavy objects or high repetition and intensity of operations). Processes: - Modification or amendment of work organization methods and improving the production planning process (repetition, constant tact, continuity), - Familiarizing staff with the use and purpose of manipulators (building a positive image of robotization) by providing an insight into the specifics of manipulator operation and a tangible example of the benefits of such implementations.
Disadvantages	Machinery, infrastructure, and equipment: - Low flexibility due to limitations on the configuration of the kinematic system, control, and operational parameters, - Large footprint (enclosed work area); low structural compactness; limited movements, speed, and acceleration; positioning accuracy dependent on the type of drives used, - Limited functionality in terms of manipulator control (sequential operation determined by the kinematic structure), - Additional handling equipment required (grippers: mechanical, vacuum, magnetic, needle); additional power source required (compressed air or hydraulic system), - Required retooling in the event of variations in the dimensions and weight of the objects to be handled. Human resources: - Required skills for basic diagnostics and repair of the manipulator, - The need to train operators and maintenance services. Processes: - The impossibility of eliminating human error in handling processes—in the case of manually controlled manipulators, - Limited increase in production efficiency indicators, - The possibility of technological debt (limited or no adaptability to future tasks; incorrect definition of performance characteristics about needs; lowest cost selection—manipulator instead of robot/cobot).

Table 4. Cont.

Level Characteristic	Description and Recommendations
Growth opportunities	Machinery, infrastructure, and equipment: • Execution of a technology audit (criteria: programming flexibility, robot–machine integration, expected efficiency, process feasibility, functional safety requirements), • Analysis of the rationale for reorganizing the structure (robotic support of individual machines, development of nests or production lines), • Implementation of robots in a selected part of the production area or full robotization (preceded by analysis or simulation).
	Human resources: • Analysis of jobs and processes in terms of whether it makes sense to replace workers with robots, • Benefit–risk analysis (creation of new job positions or competencies that may need to be supplemented).
	Processes: • Analysis of the impact of robot implementation on the scope and scale of process reorganization, • The implementation and integration of robots into the OT layer (if the level of automation and digitization of the company and the specifics of production allow it).
Development recommendations	• Implementation with the most favorable ROI, a high degree of acceptance by the workforce, and an analysis of the possibility of ensuring continuity of production (criterion for maximizing the potential of robots), • Deepening knowledge of robots and the advantages of robotization, • Preparing staff for implementation (needs analysis and level of acceptance of change), • Secure the funding for robot implementation and planning of all required activities.

Table 5. The third maturity level of process robotization (KA2-ML3)—conventional robots and/or cobots.

Level Characteristic	Description and Recommendations
Current state	Robotization of processes using programmable conventional robots or cobots: • Robot variation—conventional industrial robots and/or cobots, • Characteristics of processes’ support activities (machining, assembly, manipulation)—programmable or flexible automation with conventional robots or cobots, • Staff knowledge, competences, and skills in the field of robots—knowledge of robots/cobots (operating principle, application, operating parameters, required environmental conditions) and supplementary equipment and tools, competence in programming, maintenance, and repair, • Staff knowledge, competences, and skills in the field of industrial process robotization—ability to define the area or process of robotization, as well as the necessary parameters; the knowledge to select a robot/cobot for a specific application, • Robot–employee interaction—fenced robots, coexistence (separate workspaces with robot stopping if its zone is violated), sequential collaboration (shared workspace with workers), cooperation (shared tasks, separate workspace), or responsive collaboration (shared tasks and workspace), • Interaction and integration at robot–machine level—as in the previous case, integration of control and safety communication (digital or analog signals, handshaking, serial or parallel interfaces, industrial networks, unique interfaces); configuration possibilities: Single Flexible Machine SFM, Flexible Manufacturing Cell FMC or production lines. • Robot features and parameters: • Sensors—embedded sensors (encoders; force, torque, voltage, current sensors); optional (light, sound, temperature, contact, proximity—infrared, ultrasound, photoresistors); process sensors, including distance (ultrasonic, infrared, laser, vision systems), pressure, humidity, gas, magnetic field; safety sensors, • Communication interfaces—Common Industrial Protocols (EtherNet/IP, ControlNet, DeviceNet), Modbus, Profibus, EtherCAT, CC-Link, OPC UA, • Safety features—audits and risk assessments (installation, power system, control, mechanics, instrumentation, environment, access, incidents, human error); implementation of security functions by IEC 61800-5-2 (STO—SAFE TORQUE OFF, SBC—SAFE BRAKE CONTROL, SS1 and SS2—SAFE STOP, SOS—SAFE OPERATING STOP, SMS—SAFE MAXIMUM SPEED, SLS—SAFELY LIMITED SPEED); SAFE PROCESS DATA (SAFE VELOCITY, SAFE POSITION, SAFE TORQUE, SDI, SDO, SAI), • Possibility of remote configuration, programming, monitoring, diagnosis, and optimization—supervision and monitoring using dedicated controllers and integrated software, optional remote monitoring (dependent on the communication interface), • Mobility mechanisms—N/A, possibility of expansion with an additional robot axis (linear transfer unit), • Vision systems—optional, used when justified (quality control, assembly, welding, picking and placing, palletizing, depalletizing, material handling, packaging, subtractive or additive machining), • Environmental adaptation; data-sharing tools and methods for remote maintenance and repair—N/A, • Data storage and recovery—computer stations, portable memory devices, optional in the cloud (OT/IT communication required), • Man–Machine Interfaces—Teach Pendants (online programming), computers with software (offline programming), limited control via HMI panels,

Table 5. Cont.

Level Characteristic	Description and Recommendations
Current state	• Redundancy—N/A or optional, • Application of AI methods—N/A or optional (mostly in combination with vision systems; available intelligence functions adopted on the side of optional sensors or its software), • Methods for optimizing energy efficiency—optimization of programming paths (elimination of unnecessary movements, gentle movements with minimized acceleration values, use of inertia force for energy recovery, activation of standby mode), hardware optimization (choosing the right type of robot, high-efficiency and low-friction drive motors and transmissions, use of regenerative brakes, and variable-speed drives), process optimization (adjusting cycle times, employee education, maximizing OEE), maintenance and operation level (appropriate maintenance programs, use of monitoring and energy management systems).
Advantages	Machinery, infrastructure, and equipment: • Free programming and reprogramming of motion paths while optimizing operating parameters (increasing efficiency, productivity, safety, and quality of the handled process), • Reorganization of production processes by changing the configuration and setup of machines, • Integration capability—creation of classic automated and scalable production systems, integration with Industry 4.0 technologies (creating intelligent, interconnected production systems with more excellent responsiveness and autonomy), • Increased precision and accuracy (e.g., welding, painting, assembly, machining, assembly), • Increased productivity—24/7 working, optimization of production cycle times, increased overall efficiency, • Flexibility and adaptability (within design, software, and application constraints), • Benefits of cobots or conventional robots upgraded to cobot functionalities—maintaining the required level of safety without the need for inflexible equipment (use of built-in sensors and systems for collision detection), space-saving (compact, mobile stations, no fences), ease of installation and integration into existing production systems, adaptation to small batch production (reprogramming on-the-fly, Low-Code and No-Code). Human resources: • Familiarizing employees with advanced technology (operation of robots and examples of the benefits of such implementations), • Increase occupational safety (reduction in injuries and accidents), improved ergonomics, • Risk elimination of staff shortages while creating new jobs of higher value (higher qualifications and wages). Processes: • Change in methods and organization of processes (production planning and scheduling, internal intralogistics, warehousing), improving workflow (the ability to support with business process automation tools), • Increase process agility, efficiency, and performance (minimization of time to market, maximization of quality and repeatability, increase in employee and customer satisfaction), • Long-term cost reduction (with the condition of appropriate change management), • Production scalability without significant changes to the production infrastructure, • Facilitation of the adaptation of technological innovations (advanced control systems, integration with AI systems, or the use of data analytics to optimize processes).
Disadvantages	Machinery, infrastructure, and equipment: • The need for additional equipment and instrumentation (grippers, gripper changers, specialized tools, tool changers), the provision of extra utilities, functional safety systems, and other elements required to achieve the expected functionalities. Human resources: • The need for experienced maintenance staff or rapidly available outsourcing providers and programmers. Processes: • Cost of increased productivity (hardware, equipment, and software) and associated fees (order management, production customers, warehousing, logistics, marketing, and advertising)—the need to achieve business development with stable product demand, • The need to develop and formalize procedures (in case of breakdowns, downtimes, power failures) and flexibility analysis (development of scenarios for rapid change of assortments or orders).
Growth opportunities	Machinery, infrastructure, and equipment: • Grouping of machines to build production cells or lines with the desired level of flexibility and efficiency, • Analysis of machine reconfiguration in terms of retrofitting of input, output, and buffer storage stations (achieving autonomy of operation in the long term). Human resources: • Identification of interdisciplinary team leaders (intralogistics, production, warehousing, quality control, production planning, etc.) to build flexible cross-departmental transport, • Improving knowledge and competencies in the field of mobile robots and changes in production organization due to robot implementation.

Table 5. Cont.

Level Characteristic	Description and Recommendations
Growth opportunities	Processes: - Analysis, optimization, or redesign of intralogistics processes (elimination of manual processes in transport, loading/unloading stations through integration of mobile robots or cobots), - Integration of cobots/robots via communication infrastructure at the IT level, implementation of Edge, Fog, or Cloud Computing (requirements: implementation or expansion of resilient IT infrastructure, high degree of digitalization), - Integration of mobile robots (with simultaneous integration at ICT level).
Development recommendations	- Deepening knowledge of robotic intralogistics processes and OT/IT integration (elimination of interdepartmental information silos), - Analysis of the feasibility of integrating robot data into data analytics systems (including business processes), - Preparing employees for the robotization and integration of company departments (strengthening the sense of interdepartmental cooperation), - Planning the actions required for implementation and integration, securing funding in the context of short- and long-term objectives.

Table 6. The fourth maturity level of process robotization (KA2-ML4)—mobile robots.

Level Characteristic	Description and Recommendations
Current state	Robotization of technological and intralogistics processes using mobile robots: - Robot variation—AGV (Low Lifter, Compact Lifter, Over Lifter, Multi-Purpose Lifter, Counterbalance, Straddle Lifter, Side Loader, Mini Carrier, Twin Tote Carrier, Industrial Pallet Carrier, Multi-Load Carrier, Shuttle Carrier, Maxi Carrier, customized), AMR (G2P, Directed Picking, AMP, AIV, SGV, LGV, AGC, forked, sorting, Unit Load Carrier), - Characteristics of processes' support activities (machining, assembly, manipulation)—flexible automation with mobile robots, - Staff knowledge, competences, and skills in the field of robots—knowledge enabling the selection of a robot with the required operating parameters, knowledge of the implementation requirements of mobile robots (safety, infrastructure adaptation, communication and control, navigation, connectivity, diagnostics, and repair), - Staff knowledge, competences, and skills in the field of industrial process robotization—ability to develop a project of integration (software and hardware) of the robot into the existing infrastructure, - Robot–employee interaction—responsive collaboration (shared tasks and workspace), online or offline programming, - Interaction and integration at robot–machine level—as in the previous case, Multi-Machine Flexible Manufacturing System, - Robot features and parameters: - Sensors—navigation systems, including physical paths (follow-liners—magnetic tapes, inductive cables; tags—magnetic points embedded in the floor, QR or other codes), laser guidance (laser triangulation), vision guidance, natural navigation (scan matching—SLAM, feature matching—ANT), inertial (gyroscopic) navigation, GPS; location (ultrasound, infrared, visible light or other sensors); acceleration sensors (monitoring static and dynamic forces), - Communication interfaces—Wi-Fi, OPC UA, possible use of IIoT protocols (AMQP, BLE, CoAP, DDS, LoRa/LoRaWAN, MQTT, XMPP, Zigbee, Z-Wave, LWM2M), - Safety features—specified in ISO 3691-4 (seven types of risk—mechanical, electrical, thermal, related to materials/substances, ergonomics, environment, a combination of risks); safety requirements and protection/risk mitigation measures including general requirements, environmental conditions, electrical requirements and elements with stored energy, guards and guard locking devices, two-hand controls, gear parts, protective devices, hydraulic and pneumatic systems, avoiding automatic restarts, foot protection, braking systems, speed control, automatic battery charging, load handling, stability, protective devices and complementary measures, operating modes, safety-related parts of the control system, EMC, - Possibility of remote configuration, programming, monitoring, diagnosis, and optimization—dedicated software, secure websites, and mobile applications (optional access from mobile devices and remote terminals), - Mobility mechanisms—navigation (AGV—rigid movement paths; AMR—autonomy and flexibility); obstacle avoidance (AGV—stopping and waiting for the obstacle to be removed; AMR—obstacle avoidance or rerouting, with path optimization within the mapped area); flexibility (AGV—limited, required reorganization of routes through physical interference with infrastructure; AMR—re-mapping if necessary, dynamic definition of new intermediate points and target location), - Vision systems—optional (depending on the robot's navigation system), - Environmental adaptation—low (AGV), instrumentation and algorithm-dependent (AMR), - Data-sharing tools and methods for remote maintenance and repair—N/A, - Data storage and recovery—optional, - Man–Machine Interfaces—HMI, terminals, optional (dashboards, 3D simulation and programming environment), - Redundancy—N/A or optional,

Table 6. Cont.

Level Characteristic	Description and Recommendations
Current state	• Application of AI methods—limited use for navigation in the case of AGVs (e.g., predetermined routes); traceability; optimization of parameters, performance, routes, traffic control and collision avoidance (AMRs), • Methods for optimizing energy efficiency—dependent on the type of robot, the functionality of the control system and software, the battery charging system, the infrastructure, and the use of AI.
Advantages	Machinery, infrastructure, and equipment: • Change or upgrade machines to flexible systems with easy retooling and autonomous work, • Minimization or elimination of errors resulting from interaction with the environment, transmission of information on the location of units to dispatch systems in real time, • Connectivity to management support systems (ERP, MES, WMS, etc.) to integrate logistics, production, and business processes, • Elimination of physical barriers (e.g., conveyors, assembly lines) restricting the free formation of communication paths and evacuation corridors, • Scalability and increased efficiency through the addition of mobile robots, • Improved ergonomics using lifting or rotary tables (minimizing operator movements and eliminating non-ergonomic operations), • No overloads, increased safety of loads by maintaining smoothness of movement, • Ability to operate in extreme environmental conditions (indoors and outdoors), • Energy efficiency about human-controlled machines (optimization of operating parameters and movement paths), • Optimization of battery status and lifetime (monitoring the Depth-of-Discharge parameter), • Increasing productivity using ML, AI, and cloud-based software. Human resources: • Familiarizing employees with mobile robots by providing an overview of how they work and their benefits, • Transfer from non-value-added tasks (material transport) to value-added operations (production activities), • The possibility of building production facilities in areas with low population or skilled labor supply (independence from staff shortages), • Resilience to fluctuations in demand and market disruption (reducing demand for unskilled workers and seasonal labor shortages, minimizing the likelihood of contagion and viruses transfer). Processes: • Increase efficiency, productivity, safety, and quality through robotization of workstations and processes (intralogistics, loading, unloading, handling, etc.), • Extensive optimization possibilities (reducing labor costs, controlling production flexibility, and dynamic routing), • Eliminating manual stock tracking and costly errors, and ensuring just-in-time delivery, • Optimization of inventory and material ordering processes (business processes) by integrating data from mobile units and other departments, • Optimization of storage space and automatic adjustment of storage areas, • Monitoring, control, and optimization of the workflow (flexible management strategies, optimization based on visualization or simulation), • Dynamic path optimization and priority arbitration (elimination of robot clusters, heavy traffic, and collisions), • Reduction in indirect costs (minimizing charges for lighting, cleaning services, car parking, training, and staff recruitment; elimination of human errors, optimization of KPIs).
Disadvantages	Machinery, infrastructure, and equipment: • Additional tools, IT infrastructure, and software required (collection, processing, and archiving of data), • The need to meet the extensive security requirements of ISO 3691, • Increased risk of cyber-attacks due to the connection of robots to integrated networks, sensitivity to communication disruption (continuity of communication depends on the quality and reliability of data exchange at OT/IT level), • The high complexity of robot design results in prolonged repair times or lack of reparability in the factory, • AGV limitations—the possibility of stopping when an obstacle is detected (employee intervention required), the need for route planning and location of charging stations, limiting the application to repetitive and routine activities (with a long-planned lifetime of fixed infrastructure), • Problems with integrating solutions from different manufacturers (prioritization, mission allocation, collision avoidance), • Restrictive infrastructure requirements (floors—maintaining flatness and leveling requirements, reduction in the size of construction or expansion joints, elimination of the impact of machine vibrations, surface quality, and abrasion resistance, removal of electrostatic charges; lighting and dustiness—requirements regarding the presence of particulate matter in the air and lighting intensity). Human resources: • The need to employ highly qualified maintenance staff and robot programmers (alternatively, using outsourced integration services),

Table 6. Cont.

Level Characteristic	Description and Recommendations
Disadvantages	Processes: • A high level of intralogistics organization is required (marking, parameters of communication routes, tracking of resources and products), • High initial investment costs (purchase of robots; guidance and location systems; costs of training operators and maintenance staff; costs related to improving qualifications and transferring employees to other positions), • The need to comply with the software inspection and update schedule.
Growth opportunities	Machinery, infrastructure, and equipment: • Development of reliable and secure wireless network infrastructure and OT/IT integration, • Retrofitting or grouping of machines to form autonomous production cell systems, • The use of cooperative warehouses with mobile robots. Human resources: • The possibility of AI-based decision support for automation, scheduling, and production flow control. Processes: • Introduction of a data-driven management method (if an adequate level of digitization and the required quality of data sources have been achieved), • Edge or Cloud Computing for analysis of data from the robot(s) for the optimization of production, intralogistics, and business processes.
Development recommendations	• Deepening the knowledge of Intelligent Manufacturing, Factories of the Future, Dark Factories, Manufacturing-X, • Analyzing the feasibility of integrating robot data into business analytics systems, • IT infrastructure audit needs analysis (decision support systems, automation, robotization, systems integration), • Develop a roadmap for the company's digital transformation.

Table 7. The fifth maturity level of process robotization (KA2-ML4)—autonomous/stationary robots as IIoT devices.

Level Characteristic	Description and Recommendations
Current state	Comprehensive robotization of the factory with robots as IIoT devices: • Robot variation—AMRs, conventional industrial robots, and cobots with IIoT functionalities, • Characteristics of processes' support activities (machining, assembly, manipulation)—flexible automation with robots as IIoT components (Cloud Computing, Big Data, multi-level connectivity, SSoT, automated control without human intervention, etc.), wireless connectivity and an agile production management model, • Staff knowledge, competences, and skills in the field of robots—knowledge of robots aided by the application of AI algorithms; knowledge in planning and integrating the robot into the plant's digital assets, simulation, and programming in the Digital Twin environment and hyper-automation, • Staff knowledge, competences, and skills in the field of industrial process robotization—ability to think systemically, agile process thinking, ability to design autonomous production systems, • Robot–employee interaction—responsive collaboration (shared tasks and workspace) with Augmented Reality support, online or offline programming (using AI-assisted methods), • Interaction and integration at robot–machine level—as in the previous case, Multi-Cell Flexible Manufacturing Systems, • Robot features and parameters: • Sensors—intelligent sensors (embedded in robots, machines, and process sensors), RTLS systems, • Communication interfaces—Internet, IO-Link, OPC UA, ZigBee, LoRa/LoRaWAN, Bluetooth, BLE, 6LowPan, DUST, NB-IoT, Thread, 5G campus networks, • Safety features—extended by advanced AI and ML methods, • Possibility of remote configuration, programming, monitoring, diagnosis and optimization—network services (M2M software); real-time monitoring, control and diagnostics; prediction based on AI/ML methods (datasets generated by a set of robots—operational and environmental data, exploitation patterns; prediction at individual and holistic level); overview of circuits, location, and status; activation and deactivation of the standby function during periods of inactivity (energy saving); monitoring and identifying incidents to enable immediate action and resolving problems; application of statistical methods to optimize the production process; management of equipment tasks and their optimization according to set priorities; creation, configuration, and modification of magnetic navigation circuits' tag certification, user supervision, and revision management); tools for creating, configuring, and modifying navigation paths, • Mobility mechanisms—full autonomy in the working environment, • Vision systems—optional (depending on the required functionality), possible data acquisition from external sources (e.g., CCTV), • Environmental adaptation—supported by AI/ML, data exchange with WMS, WCS, WES, ERP systems, • Data sharing tools and methods for remote maintenance and repair—software for cooperation with integrators and service providers; creation of digital checklists and maintenance scenarios; definition and assignment of maintenance intervals; managing, recording, and documenting primary data to optimize inspections; digital files of the robot (robot life cycle documentation, data management, and decision making); smart notifications,

Table 7. Cont.

Level Characteristic	Description and Recommendations
Current state	• Data storage and recovery—clouds, servers, magnetic tapes, • Man–Machine Interfaces—dashboards and APIs, • Redundancy—hardware, software, data, network, and power, • Application of AI methods—support for monitoring, control, steering, and optimization; decision making; data processing, • Methods for optimizing energy efficiency—optimization of operating and routing parameters.
Advantages	Machinery, infrastructure, and equipment: • Autonomous intralogistics system combined with automated and robotic production, storage, and digital information flow throughout the company, • Connectivity (transparent process analysis, optimization of programming methods, real-time programming, process data monitoring), • Mandatory diagnostics and prediction (scheduling of maintenance and repairs based on current operational status; improving safety by identifying irregularities and implementing safe behavior scenarios, reduced downtime, increased productivity, and OEE). Human resources: • Minimization of employee participation, • Reduction or total elimination of human error (including cyber security risks). Processes: • Increase quality, safety, reliability (improving internal and external supply chains), and flexibility (adaptation to changes in demand—in real time), • Monitoring, controlling, and maximizing operational efficiency (the elimination of manual tasks and functions in favor of automated and digital solutions; data-driven decision making; tracking of individual objects and their groups—full utilization of the resource potential; process optimization—in terms of performance and scheduling, consumption of utilities, other costs), • Reduced time to market (more effective decision making in response to market fluctuations, better insight into supply chains, reduced response time to disturbances, identification, and elimination of inefficiencies), • Holistic standardization within the application of Digital Process Twins, • Streamlining maintenance and repair processes (provision of parts, sub-assemblies, components, consumables on time; dynamic estimation of budgets), • Advanced production monitoring methods (maintaining the serviceability of resources, quality management, safety and health of workers, production planning and scheduling, process optimization), • Intralogistics and storage operations—monitoring asset parameters (status, current and total efficiency, failure rate, location) and processes (compliance with agreed schedules, bottlenecks, delays), • Supply chains—monitoring deliveries, stocks, and products on the shop floor, control of storage and the required transport parameters (temperature, humidity), • External process operations—integration of external suppliers (stock stability), monitoring quality standards, and timeliness of tasks.
Disadvantages	Machinery, infrastructure, and equipment: • High purchase, implementation, and operating costs (sensors, devices, communication protocols, cloud storage, IT staff, technical support, and IIoT maintenance—including software), • The need to ensure reliable connection and communication (machines, equipment, safety systems, controllers, application software, and other required components) and communication infrastructure (ensuring consistent, reliable, and real-time data transmission, supervision, and monitoring), • Optimization of the number and type of data collected (data range, data structures, plugins, and fusion methods) for KPI evaluation purposes, • Data collection and processing required (algorithms, continuous optimization of data storage infrastructure, prioritization of safety and security through the implementation of cyber security rules). Human resources: • Highly skilled robot programmers and integrators and employees with interdisciplinary skills are required. Processes: • The need to develop a data security policy and provide the necessary technical measures, • Required specification of data management methods—scalability, upgrade management, troubleshooting without interrupting workflow, integration of internal or external resources (including Cloud Computing), standardization of interfaces (elimination of information silos), holistic and centralized policy (integration, associativity of existing resources and elimination of the risk of inconsistency and data loss), • Defining the scope of data management policies to create value for the company (minimum number of datasets, the frequency of collection, and the volume and cost of archiving), • The need for advanced software and analytics—scalable platforms, Big Data analytics, data management, and interpretation to provide reliable information.

Table 7. Cont.

Level Characteristic	Description and Recommendations
Growth opportunities	Machinery, infrastructure, and equipment: • Monitoring market trends, • Development of own standards with a knowledge-sharing policy. Human resources: • Continuous improvement, looking for tools to help automate decision-making processes. Processes: • Optimization of business processes by seeking dedicated or in-house solutions, • Focus on acquiring orders and maintaining demand for products.
Development recommendations	• Keeping abreast of changes in market and technological trends, • Continuous development of staff competencies, management, and talent acquisition, • Continuous maintenance, updating, and control of all factory systems.

A complete lack of robotization characterizes the first level of maturity. Robotics solutions are not utilized at this stage, although automated production lines and numerically controlled machines may be owned. Because all activities are performed manually by the employees, there is a significant reduction in both productivity and quality.

To advance to the next level, we need to enhance our understanding of robotics and the automation of technological processes. Furthermore, it is essential to identify the requirements for implementing industrial robots and analyze the competencies of human resources to work in a robotic environment.

Examining the return on investment and securing funding is necessary before purchasing a manipulator or robot. When specifying criteria for an industrial robot, it is possible to skip the second maturity level and go directly to the third level. However, the choice of a specific level must be determined by the needs of a particular enterprise and the defined objectives.

The second level of maturity involves implementing an elemental manipulator to handle loading, unloading, or manipulation tasks. These solutions are appropriate for operating injection molding machines, automated assembly stations, welding, and repetitive or physically demanding labor. Typically, they are components that utilize linear drives powered by pneumatic, hydraulic, or electric systems. Due to its kinematic structure, the application is limited to simple, repetitive actions programmed by a control system. The drawback is the limited flexibility, evident in the design dedicated to a specific solution. The advantages of such solutions are their affordability, ease of use and maintenance, and the lack of specialized knowledge required to operate them.

It is important to note that specialized manipulators are cost-effective only in mass production. The lack of rapid reconfiguration of the structure and reprogramming and the limitations of the control systems predispose them to the role of rigid support elements for robotics. In the case of unit production, line reconfiguration, or frequent changes in the production profile, it is advisable to advance to maturity level three. The trend among manufacturing companies is to eliminate rigid and non-reconfigurable manipulation devices.

To achieve a third level of maturity in implementing a manipulator (as opposed to a robot or cobot), it is recommended that the rationale behind this decision be analyzed, employees be prepared for the changes in organization and working methods, and the needs and requirements of the unit being implemented be identified.

The third level of maturity refers to using traditional industrial robots or collaborative robots (cobots). Entrepreneurs commonly choose this level; however, selecting the appropriate type of device can lead to significant improvements.

With traditional robots, the staff must possess proficiency in programming, reprogramming, maintenance, and repair. On the other hand, cobots require additional software or hardware components dedicated to programming specific applications (e.g., welding). In this scenario, it is enough to provide training on using the solution through a bench approach. When it comes to conventional robots, it is necessary to have suitable safety systems

in place. Level three only includes stationary units in enclosed production workstations or collaborative robots; mobile robots are not included. The level thus covers the classic applications of robots to perform technological, assembly, and manipulation operations directly at workstations (adding an axis could allow for movement, but its ability to move is limited). The deployment of mobile robots is becoming increasingly common in intralogistics as they fill the labor shortage gap in internal transport operations. The recommended developments include deploying wireless communication network solutions, eliminating information silos, conducting a needs audit, and optimizing intralogistics processes.

The fourth level of maturity involves using AGV/AMR mobile robots for transportation, handling, loading, and unloading purposes. To transition to the mobile robot level, it is essential to integrate with existing OT and IT infrastructure. This involves transferring data to other IT systems to manage business processes in the short term. Robots collect data for advanced analysis and integration into company process management systems. Connecting with WMS, MES, or ERP systems to schedule and delegate tasks is possible. For mobile units, there are additional requirements beyond platform selection. These include navigation systems, power supply, recharging methods, and adapting existing shop floor infrastructure to meet regulations.

A commonly overlooked issue is the improper management of material and product flows between production sites and warehouses. Implementing mobile vehicles without proper intralogistics organization is a common mistake that hinders investment and development. Under certain circumstances, reorganizing the machine setup or grouping into production cells may be required.

It is also necessary to organize and optimize the space of the production facilities (separation of storage bays, designation of staging and loading areas, setting up of additional inter-operational storage facilities, and reorganization of working methods).

The type of mobile vehicle chosen determines the kind of navigation system needed. Physical paths (following lines—magnetic guide tape, inductive cable; markers—magnetic points embedded in the floor, QR codes, or other types of codes) usually interfere with the existing construction of the production facilities (marking out planned movement routes). Laser guidance (laser triangulation), vision guidance, natural navigation (scan matching—SLAM, feature matching—natural feature navigation ANT), inertial navigation (gyroscopic), and geo-guidance require the preparation of infrastructure for data exchange and robot integration. In vision systems, it is crucial to eliminate dust and harmful fumes. The method of charging and battery replacement is vital. Battery replacement can be manual or automatic, and charging can be automatic contact or wireless inductive. One frequently overlooked criterion is the quality and deviation of the floor, as well as the size of expansion gaps and the floor's load-bearing capacity. When implementing mobile units, it is essential to consider integrating robots with existing OT/IT infrastructure, warehouse management, or other production systems.

Using autonomous or stationary robots as IIoT devices may mark the final stage of industrial maturity. In this case, the mobile robot can gather information and connect to other machines for real-time monitoring and diagnostics (possible use of AI/ML algorithms). One of the additional features is to analyze data from the units, identify patterns, and optimize processes.

Devices classified at this level allow remote operator access via dashboards and the Digital Twin. The primary advantage of configuring a robot as an IIoT device is its simple integration into existing digital systems. This enables full bi-directional data exchange functionality and a digital shell compliant with RAMI 4.0 architecture [64–69]. Thanks to advanced analytics, it is possible to determine not only performance indicators but also those relating to environmental impact and the development process of the entire company within the framework of the adopted continuous improvement plan.

Section 3 presents the research results conducted to assess the level of maturity in the robotization of production processes.

3. Results

The method was used to evaluate the maturity of 200 Polish manufacturing companies. The surveyed entities belonged to small and medium-sized enterprises (SMEs) and operated in diverse sectors. These sectors included food, chemicals, textiles and clothing, electronics, machinery, wood and furniture, packaging, household appliance manufacturing, and suppliers of components to the automotive industry.

SMEs are the largest employers and contribute the most to EU development. However, their development needs help accessing capital, external funding sources, modern technology, innovation, and a highly skilled workforce. A disruptive factor is more familiarity with modern process management methods.

In each case, the company has been classified into the described group based on fulfilling the following conditions: having less than 250 employees and an annual turnover of not less than EUR 50 million or an annual balance sheet total of not more than EUR 43 million.

The participants who responded were individuals with managerial or decision-making positions in investment planning, corporate digital vision, and strategy creation. During the survey, we identified the current level of maturity in a key area and defined a target state for the next three years.

Table 8 summarizes the study on initial and target maturity levels for robotizing technological processes.

Table 8. Summary survey of the initial and target maturity levels in robotization of production processes.

Maturity Level	Initial Maturity Level	Target Maturity Level	
		Maintaining the Current Level	Moving to the Next Level
KA2-ML1	66%	14%	-
KA2-ML2	8%	-	10%
KA2-ML3	26%	18%	50%
KA2-ML4	-	-	8%
KA2-ML5	-	-	-

According to the survey results, 66% of the respondents reported having no robots in their organization. Maturity level KA2-ML1 characterizes this lack of robotization. Only 14% of SME representatives are not planning any changes around industrial robot implementation, remaining deliberately at the first level of maturity. However, the group surveyed does not exclude entrepreneurs who own CNC and PLC-controlled machines.

The absence of change is determined by the nature of the production process, which includes its inherent characteristics as follows:

- Type of production—most often unit production with low production volumes (with a high degree of variability and customization) that require frequent development of new robot programs or modifications to existing ones;
- Lack of a consistent supplier who can provide production orders regularly;
- Difficulties in planning material supply and production due to the high variability in orders;
- Aspects related to the factories' locations—e.g., the need for local integrators and partner companies offering support in servicing the robots or employees with the right level of competence.

According to the survey, 10% of the respondents plan to use manipulators in the coming three years. This indicates a shift from KA2-ML1 to KA2-ML2. These manipulators' applications include integration in automated assembly or machining stations. Such integration is dedicated to specific parts produced on a large scale for customers with long-term contracts.

In total, 42% of respondents plan to upgrade to level three by integrating industrial robots or cobots. This exhibits well-structured production processes and seamless integration of machines with industrial robots.

At maturity level KA2-ML2, it was determined that the utilization of manipulators was at 8%. Enterprises with manipulators declared they will no longer install these units in their factories. All those declared at this level indicated a planned transition to level three (KA2-ML3). The primary reasons for replacing manipulators with freely programmable industrial robots were the limited functionality of manipulators, rigid structure, reprogramming difficulties, low productivity, inefficiency, and lack of flexibility.

According to a recent survey, 26% of the respondents reported that their companies use either conventional industrial robots or cobots. However, 18% of companies plan to stay the same, and 8% intend to move to automated intralogistics, achieved with mobile robots (level KA2-ML4). Decided enterprises have modern infrastructure and production halls that eliminate some barriers inhibiting the implementation of mobile units.

None of the surveyed companies plan to move to the fifth maturity level (KA2-ML5) due to the need for significant investments, which remains a major barrier to SME development.

Production process robotization maturity level measures are summarized in Figure 8.

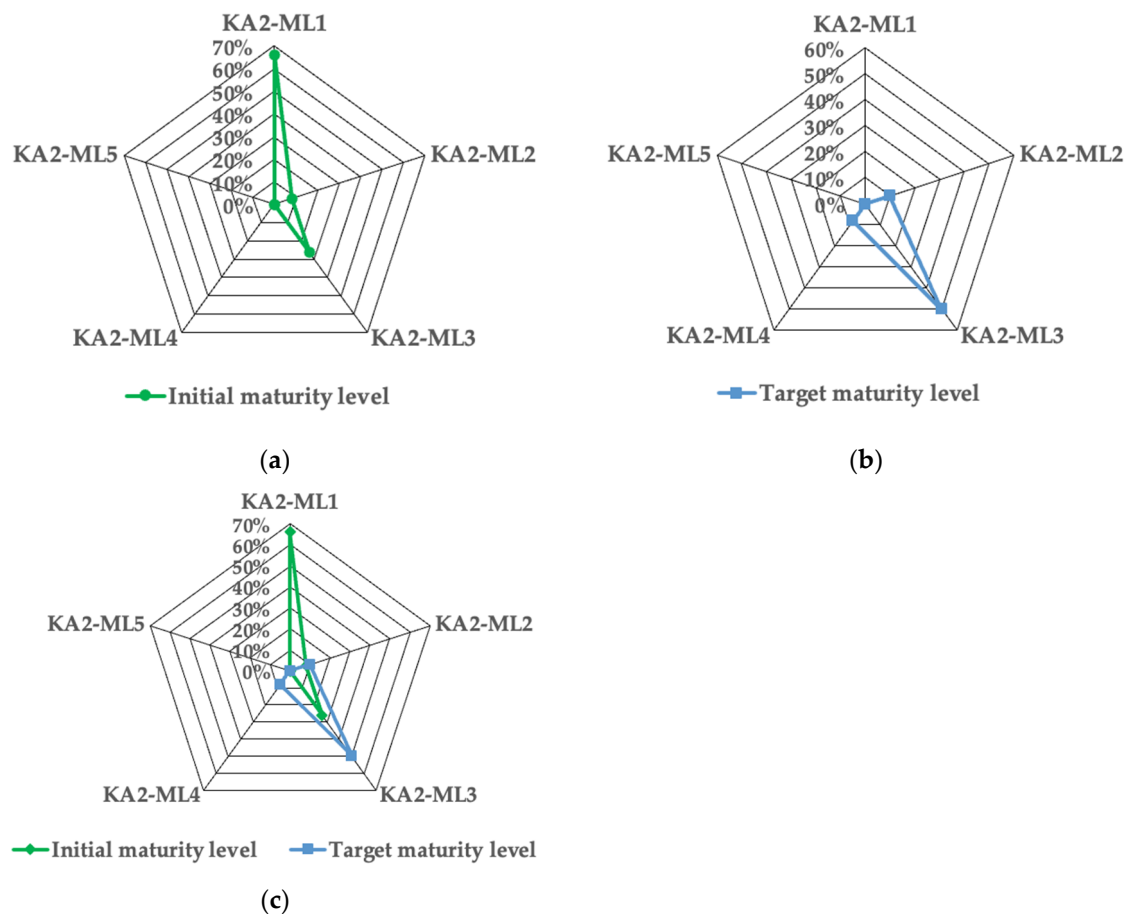


Figure 8. Summary of maturity level measures in the key area of the robotization of production processes: (a) initial maturity level, (b) target maturity level, (c) summary comparison.

The transition rate between different maturity levels can also be used to conclude that the surveyed companies primarily focused on robotization using traditional industrial robots or cobots. This state-of-the-art technology is integrated with the existing machinery and infrastructure. By retrofitting with industrial robots, the production facilities can increase productivity, repeatability, and quality with minimal capital expenditure and reorganization.

Of all the respondents, 32% plan to maintain their current level of automation in their processes. Of the entities considered, 26% already have solutions involving manipulators or robots/cobots and 26% of SMEs plan to increase their maturity level by one, but a significant 42% aim to increase their maturity level by two on the scale.

Table 9 summarizes the percentage transition rate between the different maturity levels.

Table 9. Summary of the transition rate between different maturity levels.

Maturity Level	KA2-ML1	KA2-ML2	KA2-ML3	KA2-ML4	KA2-ML5
KA2-ML1	14%	10%	42%	-	-
KA2-ML2	-	-	8%	-	-
KA2-ML3	-	-	18%	8%	-
KA2-ML4	-	-	-	-	-
KA2-ML5	-	-	-	-	-

Figure 9 shows the transition rate between different maturity levels based on the data from Table 9.

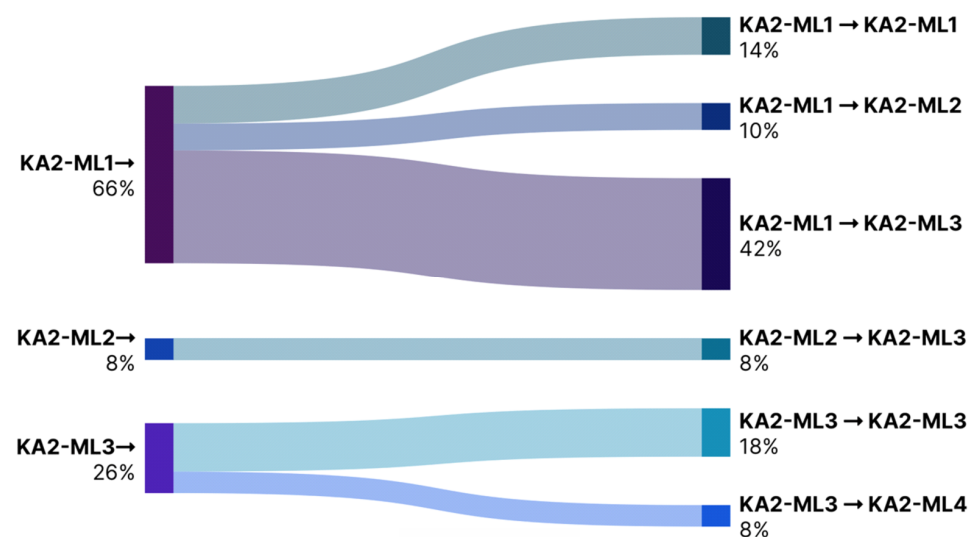


Figure 9. Diagram of the transition rate between different maturity levels.

Taking a holistic approach to research findings, SMEs are moving towards a logical strategy of robotizing their processes while prioritizing flexible and scalable infrastructure based on conventional robots or cobots.

4. Discussion

It is worth mentioning that all participating companies have familiarized themselves with the Advanced Manufacturing digital maturity survey methodology [70]. The ADMA covers seven areas of transformation, including those shown in Figure 10, to provide a comprehensive analysis.

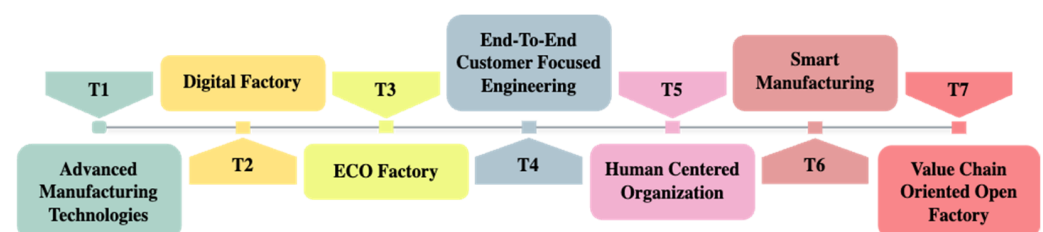


Figure 10. Transformation areas defined within the Advanced Manufacturing methodology.

ADMA offers insights into a manufacturing company's processes and opportunities for digitalization, streamlining, and optimization.

The ADMA methodology emphasizes the digitalization of manufacturing companies by implementing specialized IT solutions.

When small and medium-sized enterprises (SMEs) perform an ADMA scan, they often try to focus on all aspects of the transformation process. However, they tend to overlook the workload and costs associated with upgrading their employees' competencies, integrating hardware and software, ensuring adequate cyber security, dealing with technology dependencies, managing changes in employee roles, maintaining new machinery and equipment, and complying with environmental regulations, managing sensitive data, and protecting the company's intellectual property. The diagram in Figure 11 shows the main issues in the transformation areas of the ADMA methodology.

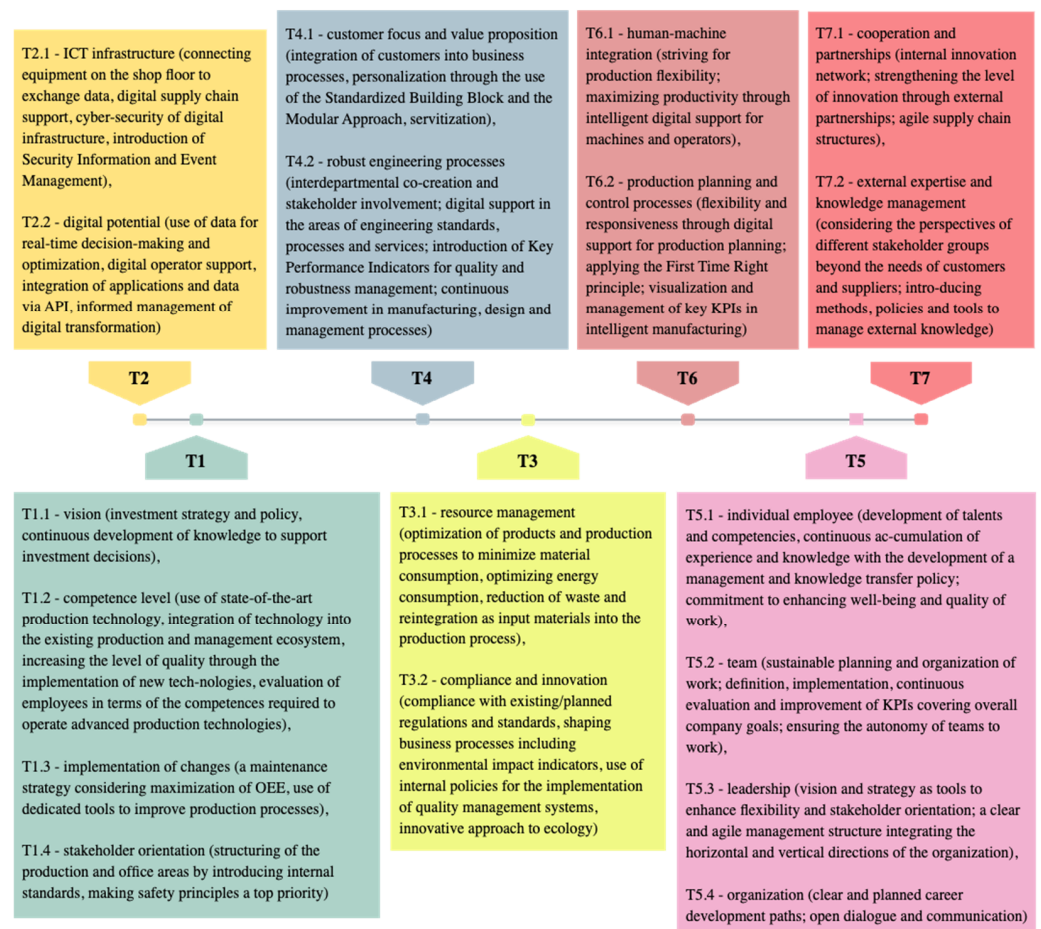


Figure 11. Key issues in the ADMA methodology transformation areas.

The author's method outlines key areas of development for companies to ensure business continuity and gain a competitive advantage while adhering to the ADMA methodology. The method proposed in this article provides a targeted approach to specific areas of factories that complement ADMA.

In the next stage, the study analyzed the impact of robotizing production processes on the development of other areas. The main goal was to pinpoint the key areas related to the robotization of production processes. Entrepreneurs have identified areas where robotization maturity is forecast to increase and should be included in development plans.

Figure 12 presents the analysis results of key enterprise areas developed due to the growing robotization of production processes.

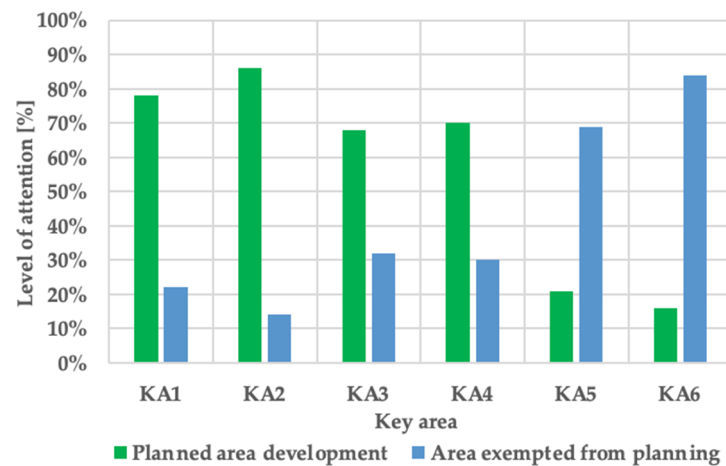


Figure 12. Level of interest in individual key areas of manufacturing companies, where KA1 is the automation of production processes, KA2 is the robotization of production processes, KA3 is the digitization of warehouse processes, KA4 is the flexibility of production systems, KA5 is the intralogistics of production processes (inter-station and inter-department transport), and KA6 is the integration of management, production, quality control, intralogistics, and warehousing systems.

A total of 86% of survey respondents plan to further develop production process robotization (KA2). Surveys indicated that investing in the automation of industrial processes is necessary for implementing robotization, as seen in the desire to develop area KA1 (78%). In total, 70% of the respondents identified increasing production process flexibility (KA4) as an area for improvement. Three previous areas influence the need to develop digitalization of warehouse processes. According to a recent survey, 68% of the respondents consider KA3 a crucial area for advancing robotics (KA2).

The integration of management, production, quality control, intralogistics, and warehousing systems (KA6) was indicated for long-term realization. A total of 21% of respondents noted the need to improve intralogistics (KA5), but solutions are being developed to streamline current processes.

Figure 13 shows the interest levels in each ADMA transformation, indicating a long-term (5-year) perspective.

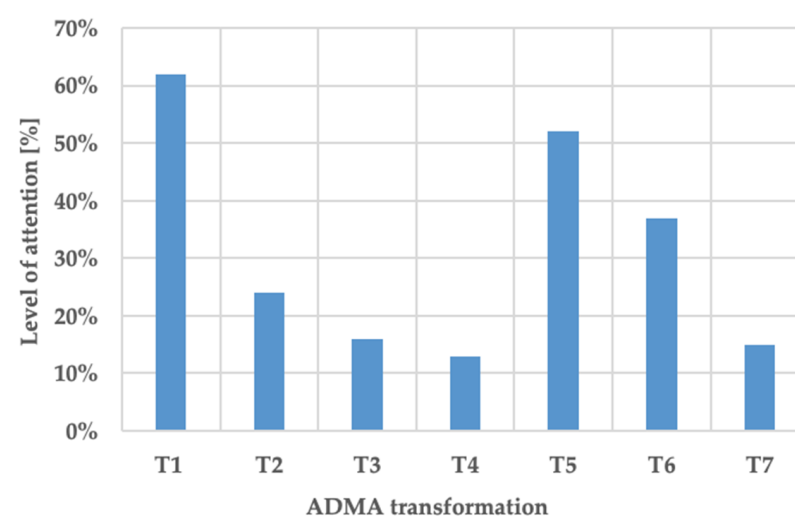


Figure 13. Level of interest in individual ADMA transformations, where T1 is the Advanced Manufacturing Technologies, T2 is the Digital Factory, T3 is the ECO Factory, T4 is the End-To-End Customer-Focused Engineering, T5 is the Human-Centered Organization, T6 is the Smart Manufacturing, T7 is the Value Chain-Oriented Open Factory.

The development of robotization changes priorities from a long-term perspective. According to the entrepreneurs interviewed, the development roadmap should be directed towards advanced technologies in robotics (T1, 62%), the development of a human-centered organization (T5, 52%), and the transition to Smart Manufacturing (T6, 37%). The holistic digitalization described by the T2 transformation is receding into the background due to infrastructure development at the Operational Technology level. The decline in customer-driven engineering (T4) is tied to companies' possession of technologies classified to the areas of transformation.

Table 10 presents the primary development directions of the companies within the surveyed industries.

Table 10. The fundamental development directions of the industries being surveyed.

Industry	The Focus for Robotization Development
Food	Packing and palletizing are the current needs, while cleaning and disinfection are planned implementations.
Chemicals	Cleaning, handling, packaging, palletizing, and inspection.
Electronics	Palletization, robotic assembly (retrofitting robots with vision systems), test benches for finished products.
Machinery	Robotization of CNC machines and inter-station storage.
Wood and furniture	Support for manipulation between automated production machines (stationary robots).
Packaging	Inter-station transfer, palletization, and packaging of finished products.
Household appliance manufacturing	Intralogistics and inter-station transport, transfer between presses.
Suppliers of automotive components	Robotization of CNC machines, automated lines, manufacturing cells, inter-station storage, and inter-station transport.

Table 11 contains guidance for entrepreneurs on applying the proposed maturity assessment method [26–29] to address concerns outlined in the Industry 4.0/5.0 definition.

Table 11. Guidance for entrepreneurs in the case of guidelines outlined in the Industry 4.0/5.0 definition [26–69].

Area	Sub-Area	Application in the Proposed Method
Synergistic integration of trends in engineering and technology (A1)	Artificial intelligence (A1.1)	Integrating artificial intelligence in robotic systems aims to optimize process flows, reduce energy, and input material consumption, eliminate production downtime, and efficiently allocate resources, controlling autonomous robots and integrating them into automated systems.
	Real-time connectivity and data exchange (A1.2)	Increasing machine reliability and lifespan by monitoring operating parameters, providing digital support for operators, and implementing standards for future machine upgrades; supporting robot motion and monitoring parameters and performance.
	Flexible automation (A1.3)	Increased speed of response to market demands with fewer specialized units, elimination of the need for continuous machinery and equipment replacement, and increased quality of work through digital support.
Market development (A2)	The circular economy (A2.1)	Conscious implementation of robotization to minimize errors, optimize movements and paths (criteria for minimizing energy consumption), and protect workers' health and lives.
	Personalization and customization (A2.2)	Increasing response dynamics to market needs, developing flexible production close to customers to reduce transport costs and carbon footprint.
	The sharing economy (A2.3)	Using the maturity level evaluation method while retrofitting equipment and adopting Robot-as-a-Service reduces the threshold for entry into new technologies and allows testing solutions without the need to purchase.

Table 11. Cont.

Area	Sub-Area	Application in the Proposed Method
Social and environmental changes (A3)	Global warming (A3.1)	Increasing the importance of informed machinery and equipment selection, considering extended service life, retrofitting options, and future integration into management systems.
	The digitally connected society (A3.2)	Implementing employee-friendly technology to reduce information overload and increase comfort by generating clear and readable reports without significantly increasing employees' workload.
	Lifestyle and demographic changes (A3.3)	Application of flexible automation and robotics in processes with staff shortages and tasks involving repetitive activities.

5. Conclusions

The presented approach aims to help entrepreneurs achieve digital maturity for their company by improving the automation of the production process. The digital transformation process involves designing, managing, optimizing, and monitoring business, production, and logistics processes to implement continuous improvement and sustainability practices. The objective of digital transformation is to attain a state of digital maturity. The term can be described as a measure of an organization's ability to create value by integrating organizational operations and human capital with digital processes, leading to increased responsiveness to the development of products, processes, business models, and marketing innovations. The correct implementation of change requires digital awareness, which determines the possession of the knowledge, skills, and attitudes needed to use digital tools effectively.

The method presented in this article was developed for small and medium-sized enterprises but is not limited to this type of entity. The primary objective was to address the issues in the first ADMA transformation (i.e., Advanced Manufacturing Technologies).

Entrepreneurs were surveyed to identify the principal risks and barriers associated with digital transformation as follows:

- Lack of clear strategy and vision—lack of a defined direction for change, tools, and methods to set short and long-term goals;
- Resistance to change—employees' fear of being replaced by modern technology, fear of increasing productivity and quality levels;
- Lack of understanding or acceptance of the culture of innovation—fear of creative and out-of-the-box thinking, lack of open communication and team collaboration;
- Lack of consistency in change management and communication—lack of adequate change management, competency gaps, inadequately mapped staff resources, lack of teams responsible for the different stages of the transformation and their scope, lack of measurable indicators and assessment of unforeseen risks;
- Lack of resources and support—lack of a change leader, staff with the right competencies and skills, lack of integrators or subcontractors;
- Changes in areas of the company's operation—new production technologies, changing management methods (disintermediation, data-driven decision making, reorientation of revenue streams, regulatory challenges, need for continuous learning and development, ensuring cyber security and data privacy, the introduction of performance indicators and KPIs for evaluation purposes), employees (automation of tasks, remote and flexible working arrangements, reskilling and upskilling, digital channels for collaboration and communication, changing job roles and responsibilities, emphasis on innovation and creativity, greater professional autonomy, changes in work culture, potential job change);
- Breach of data confidentiality and security, loss of know-how—lack of security policies, software, and hardware protection;
- Difficulties in integration with existing systems—lack of use of standards and consideration of scalability requirements of systems under development;
- Budgetary constraints—lack of funds or purchase of solutions with redundant and underutilized functionality;

- Regulatory and compliance restrictions—maintaining the guidelines of norms, regulations, and standards;
- Existing systems and infrastructure—constraints related to integration and incorporation of newly designed technical systems;
- Supplier dependency and interoperability issues—problems of factory locations, lack of support, and local integrators.

Robotization is a crucial addition to automation and CNC machining processes and a fundamental part of modern intralogistics for mobile units. Retrofitting with collaborative robots allows for the flexible shaping of production flow characteristics and movement paths. The described functionalities provide flexibility, enabling optimal shaping of the machine's load and reinforcing their functionality and utilization.

Small and medium-sized enterprises in Poland are among the entities that need to start using robots at the current development stage or applying conventional industrial robots to operate technological processes. The metalworking industry is the sector that uses industrial robots the most, where the cost and degree of robot adaptation are the lowest. There is a growing trend to use easier cobots in applications that do not require complex integration with machine tools.

Companies are also choosing to use mobile vehicles to a lesser degree. In most cases, AGVs are abandoned in favor of Autonomous Mobile Robots. In addition, mobile units are being adapted in newly built factories or production halls because the infrastructure can be designed accordingly. Increasingly, robots are being seen through the lens of corporate sustainability, as they allow for increased comfort at work and move workers away from dangerous or strenuous work.

At this stage of development, robotization is not a solution available only to large companies; market changes and the introduction of the Robot-as-a-Service business model have significantly lowered the entry threshold to a level of investment possible for small and medium-sized enterprises.

Another aspect of the robotization event is the possibility of a comprehensive pre-implementation simulation of the designed solution using Digital Twins, which are also used for monitoring and diagnosing existing implementations.

Robotization goes beyond the areas initially defined, and its position in the industry needs to be addressed. The development trends aim to boost the application of industrial robots and cobots.

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