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A Structured Methodology for Synthesizing Parameters and Architecture of Robotic Technological Systems in the Digital Transformation of SME Engineering Production

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Abstract

INTRODUCTION: Robotic automation has become a key driver of digital transformation in the engineering sector, especially for small and medium-sized enterprises (SMEs), which face increasing demands for flexibility, efficiency, and cost optimization. However, most classical automation frameworks do not address the structural and economic limitations specific to SMEs. Despite recent advances in modular automation, a gap remains in methodologies tailored to low-volume, high-mix environments typical of SMEs.
OBJECTIVES: This paper aims to develop a structured methodology for synthesizing the parameters and architecture of robotic technological systems adapted to the production realities of SME engineering environments. The goal is to balance automation effectiveness with practical investment constraints.
METHODS: The proposed approach integrates a multi-level automation model with production system analysis, considering object-specific constraints, part characteristics, and process parameters. The methodology was validated through an expert- and data-driven case study of a Ukrainian SME engaged in serial plastic part machining. Functional-cost analysis and feasibility modeling were used to evaluate automation options. In addition, investment-efficiency mapping was introduced to support strategic planning of implementation phases.
RESULTS: The implementation of the proposed system, based on a six-axis robotic manipulator with digital control and vacuum clamping devices, led to a 50% reduction in auxiliary processing time, improved consistency, and reduced labor intensity. The workplace-level automation enabled flexible part handling without the need for major structural changes or high capital investment. The system demonstrated high adaptability to part variations and required minimal operator intervention.
CONCLUSION: The developed methodology provides a scalable and economically viable path to robotic automation for SMEs. It supports gradual implementation and can be further enhanced by integrating artificial intelligence tools for decision-making during system design and optimization. This structured framework contributes to the digital resilience of SME manufacturing and aligns with Industry 4.0 principles.

Keywords: Robotic Automation, SME Engineering, Process Synthesis, Digital Transformation, Technological Systems, Workplace Design, Industry 4.0.

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1. Introduction

The convergence of mechanical engineering and digital technologies has led to a new paradigm in industrial production, characterised by the widespread introduction of robotic systems and intelligent automation. As global

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manufacturing transitions to Industry 4.0, small and medium-sized enterprises (SMEs) are increasingly recognised as essential players in maintaining competitiveness, adaptability, and innovation potential in the mechanical engineering sectors. However, SMEs often face significant barriers to adopting advanced automation technologies due to limited financial, spatial, and human resources.

Unlike large manufacturers, SMEs operate in more constrained environments where cost-effectiveness, production flexibility, and rapid adaptation to customer requirements are critical. Consequently, the implementation of automation systems in such enterprises requires not only technological feasibility but also strategic alignment with operational realities. Traditional automation models, which focus on full system integration and high-performance solutions, often prove impractical or economically unjustified for SMEs. Recent advances in modular robotics, digital process control, and intelligent manufacturing services have enabled the development of customisable, scalable automation architectures that meet the specific needs of small-batch production. In addition, workplace-level automation, which is often overlooked in traditional automation hierarchies, has become a practical and effective starting point for gradual implementation. By carefully considering product characteristics, processing requirements, and process flexibility, robotic systems can enable SMEs to reduce manual labour, improve quality, and optimise production cycles without significant capital investment.

This study presents a structured methodology for synthesising the parameters and architectural configuration of robotic technological systems in SME engineering production. The methodology is designed to support decision-making based on data on the feasibility of automation, taking into account SMEs' unique structural, technological, and economic constraints. It also considers integrating digital services at various levels of the automation hierarchy and explores how step-by-step implementation strategies can increase adaptability and reduce risks during technological transformation.

The proposed methodology has been tested on a Ukrainian SME engaged in processing complex plastic components. By analysing production structures, processing tasks, and material properties, the study demonstrates how robotic automation based on a six-axis manipulator can be effectively implemented in the workplace to optimise auxiliary operations and support sustainable digital transformation in engineering SMEs.

2. Literature Analysis

Automation in engineering production has long been regarded as a cornerstone of manufacturing efficiency, quality improvement, and cost optimization. Foundational works such as Groover's [1, 2] have provided detailed classifications of automation types–fixed, programmable, and flexible–and outlined hierarchical automation levels ranging from individual device control to enterprise-wide integration. These models have formed the basis of traditional manufacturing automation strategies across industries.

However, their direct application to small and medium-sized enterprises (SMEs) remains limited due to structural, economic, and operational constraints. While large-scale automation systems typically rely on rigid architectures and extensive capital investment, SMEs require more adaptable, cost-effective solutions. In this context, a growing body of literature highlights the need for customized approaches to automation tailored to SME conditions.

Modern trends in the automation of production processes for SMEs are primarily driven by the need to increase efficiency, flexibility, and product customization.

Recent studies emphasize the use of digital twins for real-time monitoring and decision support [3], reconfigurable manufacturing systems (RMS) for dynamic adaptation to changing orders [4], and hybrid automation approaches combining robotics with cyber-physical infrastructures [5]. Unlike these top-down strategies, the methodology proposed in this paper focuses on lightweight, modular deployment tailored to SMEs with constrained resources.

Several studies [6-9] have examined modular, aggregate-based manufacturing systems that offer potential for structural-parametric optimization. Although these approaches contribute to sustainability and reconfigurability, they are mostly oriented toward mass production environments and do not fully capture the flexibility demands of SMEs. Likewise, general models for manufacturing process selection [10, 11] often overlook enterprise-specific limitations such as irregular batch sizes, space constraints, and human resource variability.

More recent research has explored adaptive and intelligent automation strategies. For example, Grznár et al. [11] proposed a digital modeling framework for adaptive manufacturing systems, integrating simulation tools for process layout and resource allocation. Similarly, advanced control methodologies for maximizing productivity under quality constraints have been discussed in the context of the Internet of Production [12]. While valuable, these models generally assume the existence of robust digital infrastructure, an assumption not always valid for SMEs.

A number of works [13-16] have attempted to bridge the gap by addressing automation from the perspective of process engineering and control systems. However, they typically focus on high-level systems or centralized automation platforms, without delving into the localized implementation challenges that are often decisive in SME environments. In contrast, literature on workplace-level automation, including manipulation, tool handling, and fixture design, remains relatively sparse, despite its practical significance.

2.1 The Emerging Role of AI and ML in SME Automation

With the rapid evolution of Artificial Intelligence (AI) and Machine Learning (ML), new opportunities are emerging for SMEs to overcome traditional automation limitations. Recent studies [17, 18] demonstrate how AI-driven predictive analytics, adaptive control algorithms, and data-driven decision-making tools can improve process efficiency, reduce downtime, and enhance quality, even in resource-constrained settings. For instance, ML-based process tuning can help optimize cutting conditions in real time, while AI-assisted planning tools can suggest feasible automation configurations based on historical part and workflow data. Unlike conventional automation, these solutions can be implemented incrementally and require minimal infrastructure, making them particularly attractive for SMEs seeking flexible and scalable digital transformation.

In summary, although the literature offers a solid foundation for understanding industrial automation, there is a clear gap in methodologies that directly support the structured design and implementation of robotic technological systems within SMEs (Tabl.1).

Table 1. Comparative Analysis of Automation Approaches in Engineering Production

Approach / Source	Scope	Target Enterprise Size	Flexibility	AI/ML Integration	SME Applicability
Groover [1, 2]	System-level, fixed/flexible automation	Large enterprises	Low to medium	No	Limited
Yakimov [6], Yakovenko et al. [7–9]	Modular machines, parameter synthesis	Medium to large	Medium	No	Partial
Swift & Booker [7]	Process selection models	Universal (design-oriented)	Medium	No	Limited
Grznár et al. [11]	Adaptive systems, simulation models	Medium to large	High	Partial	Moderate
Internet of Production [12]	Digital twin-based optimization	Large, connected enterprises	High	Yes	Low
Basova et al. [19]	Digital integration, 3D visualization	SMEs	Medium	Partial	High
Sevic & Keller [20]	Smart factory (Industry 4.0 model)	Large	High	Yes	Low
AI/ML-based automation (e.g., [17, 18])	Predictive and adaptive control	SMEs and startups	High	Yes	High
This study	Robotic workplace-level automation	SMEs	High	Planned use of AI/ML	High

Particularly lacking are frameworks that integrate object-specific machining parameters, workplace-level constraints, and incremental deployment strategies. The present study addresses this gap by proposing a methodology that bridges high-level automation concepts with practical implementation at the SME scale.

Fig. 1 and Fig. 2 from the classical framework of automation types and levels are retained in this study, serving as foundational references.

However, the authors expand these frameworks by introducing the "workplace" as an independent automation level-one that is critical for SMEs pursuing stepwise digital transformation with limited resources.

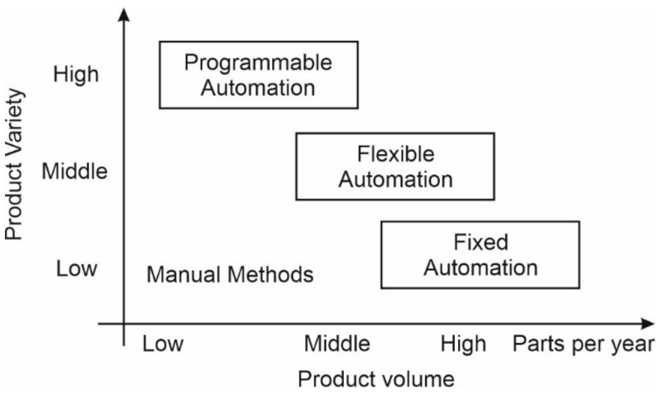

Figure 1. Types of automation in manufacturing processes

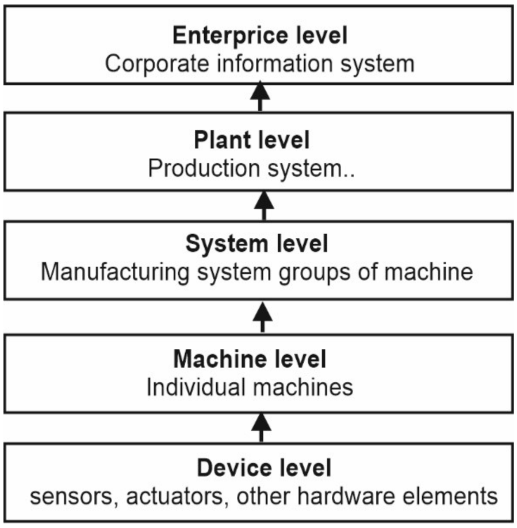

Figure 2. Levels of automation in manufacturing processes

3. Materials and Methods

This study adopts a mixed-methods approach to develop and validate a structured methodology for synthesizing the architecture and parameters of robotic technological systems in SME engineering environments. The methodology was designed to support informed, economically grounded decisions on the implementation of automation solutions under the constraints typical for small and medium-sized manufacturing enterprises.

3.1 Research Context and Motivation

The investigation was motivated by the urgent challenges faced by Ukrainian SMEs in the engineering sector, particularly in light of ongoing economic instability and wartime disruption. Many of these enterprises operate under fragmented production conditions, with limited access to skilled labor, digital infrastructure, and capital resources. In such settings, traditional automation frameworks often prove infeasible or unsustainable.

To ensure practical relevance, the methodology was tested in a real-world SME context – a machining-oriented enterprise specializing in the serial production of plastic parts. This enterprise served as the pilot site for applying the proposed framework and assessing its effectiveness in guiding automation-related decision-making.

3.2. Data Collection and Enterprise Profiling

Between August 2022 and February 2024, a multi-stage data collection effort was conducted involving 32 SMEs in the Kharkiv region. Participants included technical directors, lead engineers, and production managers. A combination of structured surveys, semi-structured interviews, and focus group discussions was used to gather detailed information about production workflows, workforce capacities, types of manufactured parts, tooling practices, and automation readiness.

The case enterprise selected for in-depth analysis had the following characteristics:

– Staff size: 35 employees.
– Primary output: plastic components (polystyrene, ABS).
– Existing equipment: hand and bench tools, basic computer numerical control (CNC).
– Production mode: low-volume, high-mix.

Constraints: limited floor space, manual labor intensity, lack of prior automation.

3.3 Analytical Framework

The proposed methodology was structured into the following seven stages:

1. Production Environment: Evaluation of the existing production system, including equipment layout, part flow, process stability, and degree of manual intervention.
2. Analysis of the geometric, material, and physical properties of the parts being produced, including dimensions, rigidity, tolerance classes, and repeatability.
3. Reconstruction or optimization of the technological process, identifying key transitions, auxiliary operations, and sources of inefficiency.
4. Development of system-level requirements based on identified production needs, including constraints on equipment footprint, tool reach, speed, flexibility, and fixture compatibility.
5. Conceptualization of several candidate automation layouts (e.g., robotic arm + power spindle + dual work tables), with varying degrees of flexibility and investment scale.
6. Each scenario was subjected to expert-based technical assessment and functional cost analysis, including Return on investment (ROI) estimation and risk assessment.
7. System Selection and Implementation Planning: Selection of the most viable robotic system layout and corresponding implementation roadmap, including specification of tooling, power units, and clamping systems.

3.4. Methodological Specifics and Tools

Assessment techniques: SWOT analysis, process bottleneck mapping, and labor time diagnostics.

Design tools: CAD modeling of workspace layout; kinematic analysis of robotic arms using RoboGuide software.

Evaluation metrics: Auxiliary time reduction, tool change minimization, operator detachment, and workstation cycle time.

Software and modeling: 3D part modeling (SolidWorks), system configuration modeling (MATLAB Simulink), and trajectory planning using robot path generators.

3.5. Role of AI and Future Integration

Although the current system design relies on expert judgment and rule-based assessment, the methodology is structured to support the future integration of artificial intelligence tools. Specifically, AI can be applied to:

– Optimize robotic trajectories for complex part geometries.
– Suggest optimal toolpath strategies based on material and feature sets.
– Perform real-time adaptation of machining parameters.
– Automate the selection of candidate automation layouts based on part families.

Such integration will further increase the adaptability and intelligence of the proposed methodology, making it suitable for dynamic manufacturing environments.

4. Results

The application of the proposed methodology was carried out at a Ukrainian SME specializing in the small-batch production of plastic components. The enterprise operated under conditions typical for engineering SMEs: irregular order flow, limited automation experience, and high reliance on manual labor for machining tasks. The goal was to evaluate the feasibility and efficiency of introducing a robotic automation solution focused on a specific production area.

4.1. Automation Strategy and Enterprise Structure

Industrial automation within SMEs typically proceeds incrementally, due to resource limitations – financial, human, spatial – and the necessity to minimize disruptions to ongoing production. As such, it is critical to select automation scenarios that offer high productivity impact with limited investment. Figure 3 illustrates this trade-off between automation level and associated financial investment.

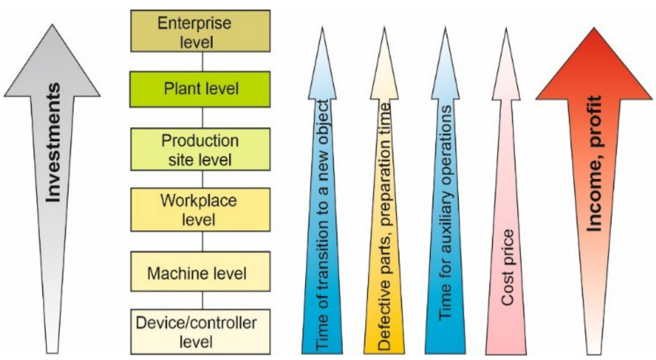

Figure 3. Levels of automation and finances

To support structured automation planning, the authors developed a multilevel model of automation that expands on the classical hierarchy by explicitly introducing the “workplace” level (see Figure 4).

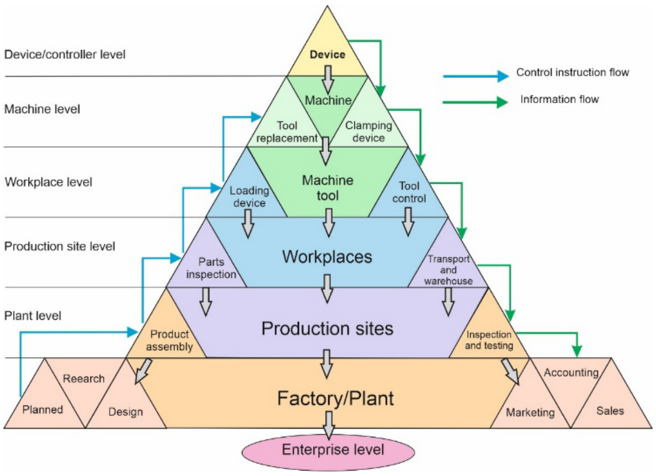

Figure 4. Structure and levels of automation of machine-building enterprises

In SME environments, automation at this level offers significant value, enabling the enhancement of processing efficiency while maintaining operational flexibility. Through modular implementation – automating material handling, processing, or quality control individually – enterprises can gradually scale their automation capacity.

Building on the principles of Industry 4.0, the study also mapped digital services and their alignment with each automation level (Figure 5). This mapping supports strategic integration of software tools, mobile platforms, and remote monitoring services tailored to the digital maturity and investment capabilities of the enterprise.

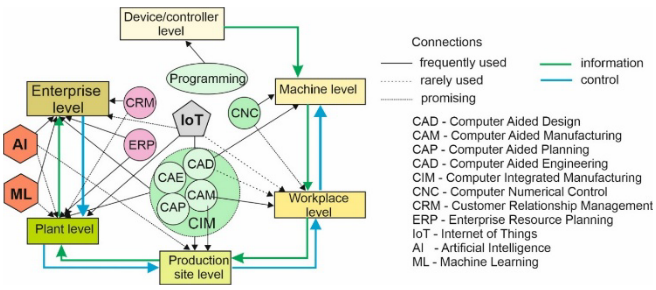

Figure 5. Levels of automation and their connection with modern digital services

4.2. Key Factors Affecting Automation Design

To guide the design of robotic systems, the authors identified and classified key technical and structural parameters affecting automation feasibility. These include:
1. Part-related parameters (material, rigidity, geometry, number of operations).
2. Process parameters (tool path complexity, setup time, cutting conditions).
3. Enterprise-specific constraints (equipment availability, part families, workforce skill level).

These parameters serve both as requirements and limitations, narrowing the range of viable automation options. Figure 6 presents a block diagram of the structured approach to synthesizing automated machining workplaces typical for SMEs. The model supports filtering of system configurations using predefined boundary conditions.

4.3. Case Study: Automation of Plastic Part Machining

The enterprise under study produces small batches of polystyrene components using basic equipment: handheld drills, saws, and templates. Processing relies heavily on manual marking and guiding, requiring highly skilled personnel and resulting in long auxiliary times (up to 70–80% of the total cycle).

Figure 7 shows representative part geometries processed at the site. These parts feature thin-walled sections, large profiles, and multiple holes, demanding both high-speed machining and accurate clamping. Given their low rigidity and surface complexity, they necessitate dedicated fixturing.

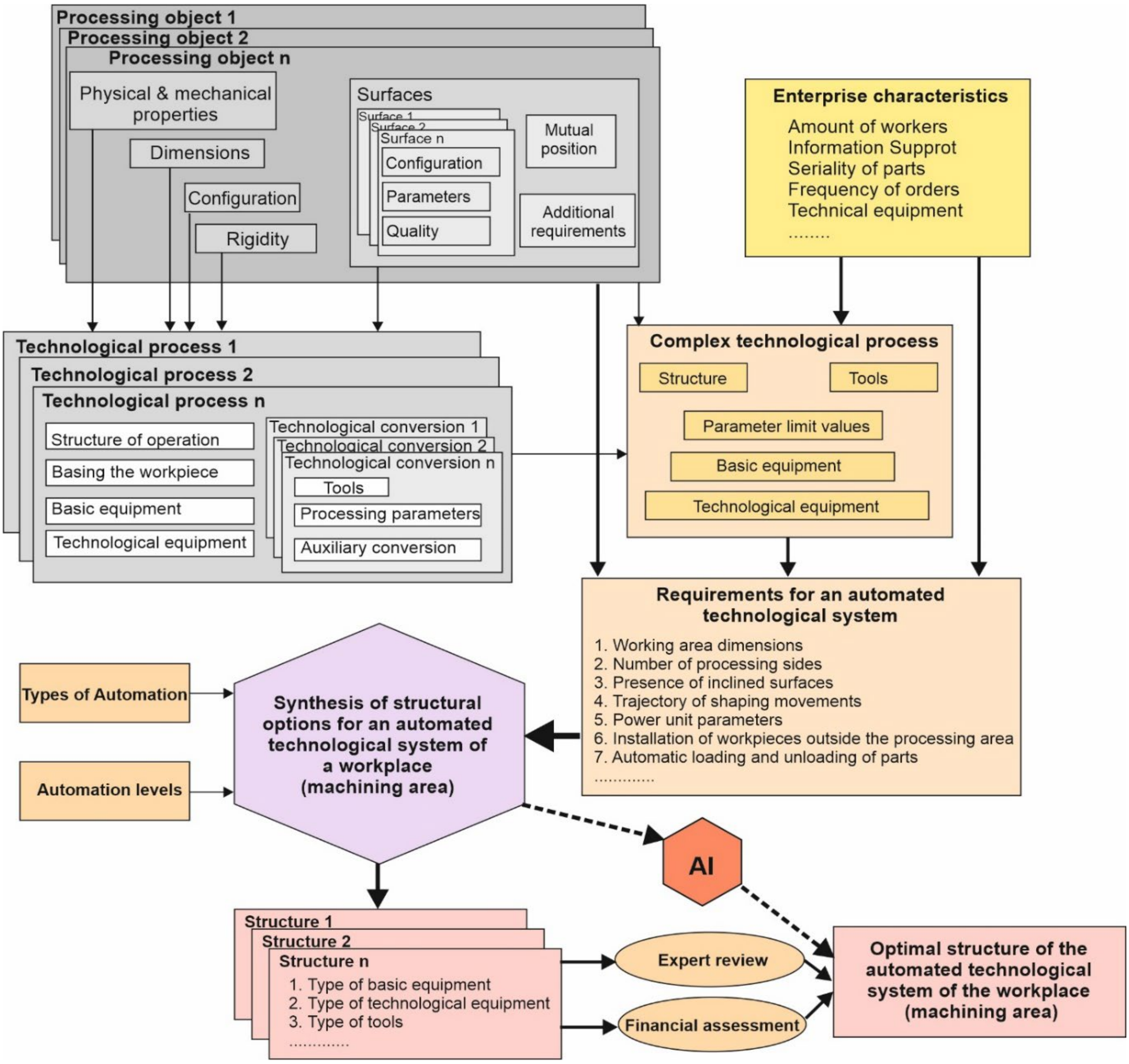

Figure 6. The process of forming the structure of an automated technological system of a machining workplace

4.4. System Requirements and Automation Proposal

Based on part characteristics, process observations, and enterprise limitations, a system of functional requirements was formulated (Figure 8). These included:

- Workspace envelope exceeding 2100×800 mm, with ≥500 mm tool stroke
- Support for multi-surface machining (up to 340 surfaces per part)
- Capability for high-speed, burr-free plastic cutting (12,000–24,000 rpm)
- Tool interchange minimization (single universal cutter preferred)
- Flexible fixturing to accommodate part diversity

Two system configurations were considered:

1. *5-axis CNC machine with a rotary table*
→ High precision, but significant capital investment and limited reusability.

2. *Robotic manipulator with a high-speed spindle and dual working tables*
→ Flexible, scalable, and more economically feasible.
→ Selected as the final configuration.

Figure 7. Representative parts processed at the plant

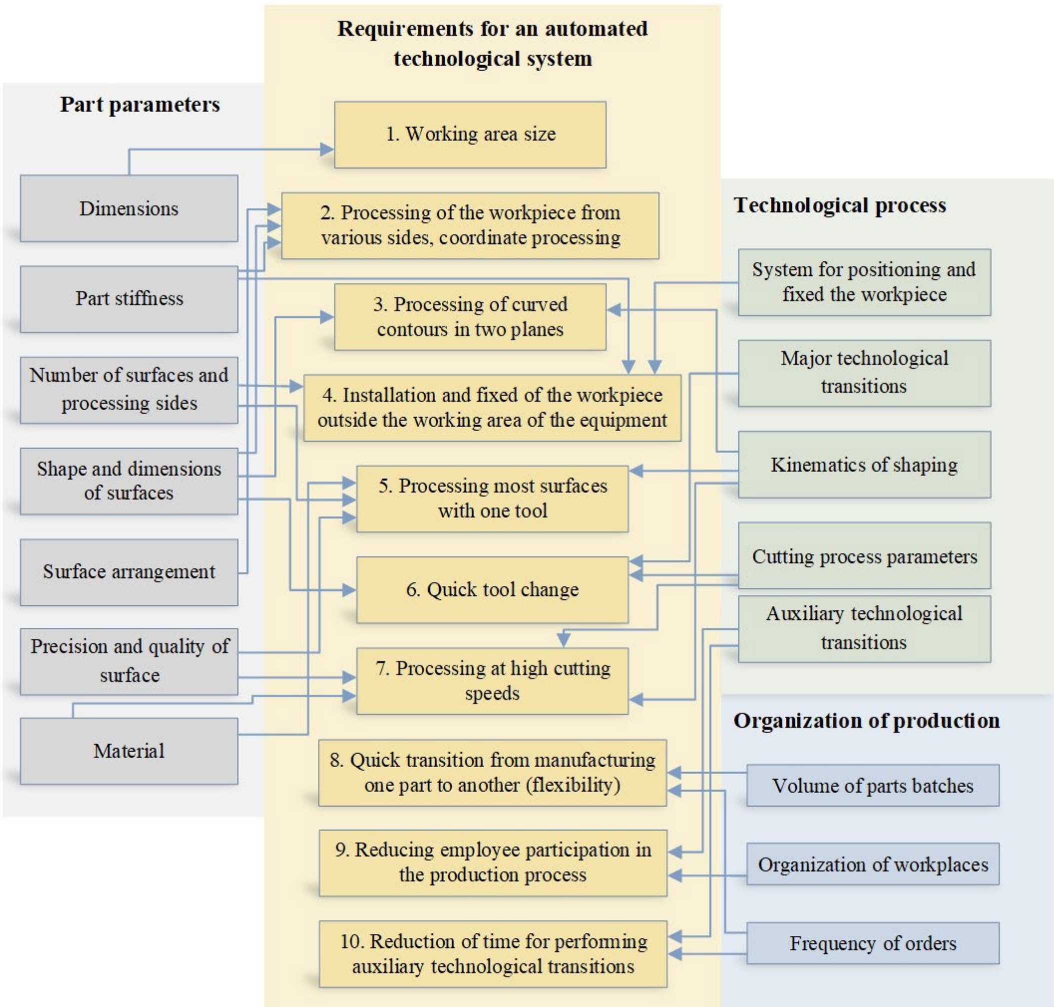

Figure 8. Structure of formation of requirements for the designed automated technological system

Figure 8 presents a simplified layout of the robotic machining cell. It includes a six-axis manipulator, vacuum clamping devices, HMI interface, and controller enclosure.

The defined working area of 2100 × 800 × 500 mm corresponds to the manipulator's operational reach, the dimensions of the pallet used for serial part placement, and the maximum envelope of the parts being machined.

The robot trajectories were generated using offline programming within the manufacturer's proprietary simulation software. CAD models of the robotic cell were used to define pick-and-place paths, safe zones, and collision avoidance. All trajectories were validated through virtual simulation and dry-run execution prior to final deployment.

4.5. Implemented System and Performance Improvement

The selected solution was based on the FANUC M-710iC/70 robotic manipulator, equipped with an HSD ES951e motor spindle (8 kW, 12,000–24,000 rpm), and custom vacuum-based clamping devices. Figure 9 shows the resulting automated workplace layout. To minimize idle time, two rotary worktables were used in parallel, allowing loading and unloading during active machining cycles.

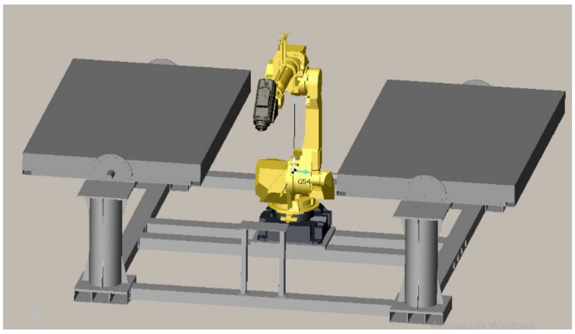

Figure 9. Automatized working place

<u>Key improvements observed:</u>

1. Auxiliary time reduced by up to 50%.
2. Operator presence was significantly minimized.
3. Defect rate decreased due to the automation of positioning.
4. System adaptable to various part geometries from the same family.

The proposed solution was initially implemented for the most frequently manufactured components. The design supports further expansion by integrating AI-driven path planning and parameter tuning modules, ensuring long-term adaptability and scalability.

The implementation resulted in a 50% reduction in auxiliary processing time and a 60% increase in effective cutting time per shift, without additional personnel.

Figure 10 illustrates the processing time distribution before and after automation, highlighting the improvements.

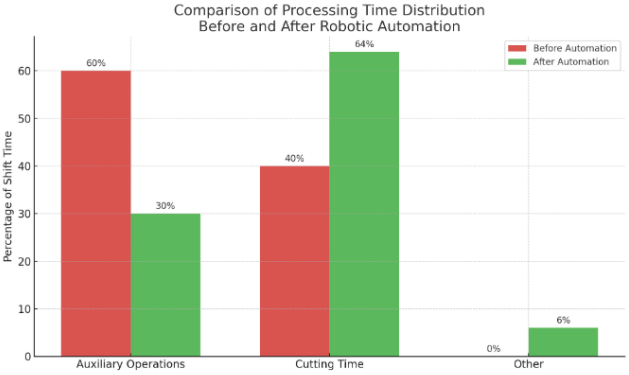

Figure 10. Comparison of processing time distribution before and after robotic automation

4.6. Investment Efficiency Model for SME Automation Planning

In addition to the technical feasibility and operational performance of robotic systems, the economic effectiveness of automation remains a key determinant of adoption in SMEs. Given the constrained financial conditions, particularly intensified in the context of post-war recovery, export reorientation, and shifting industrial priorities in Ukraine, investment planning must follow a phased, impact-driven approach.

To support this decision-making process, a general conceptual model was introduced for mapping automation solutions in the investment–effectiveness coordinate system (see Figure 11). The model was developed based on elements of SWOT analysis and comparative evaluation, allowing for the visualization of different automation modules according to their capital intensity and expected impact on production performance.

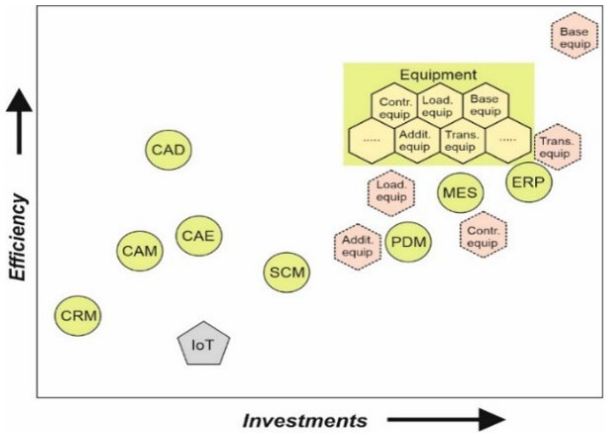

Figure 11. Prioritization model of automation components based on investment-efficiency mapping for SME manufacturing

In this scheme:

- Circular elements represent digital systems for design, planning, communication, and management (e.g., CAD/CAM, Enterprise resource planning (ERP) systems, MES).
- Hexagonal elements correspond to hardware-based automation tools for core and auxiliary manufacturing operations (e.g., robotic arms, automated inspection, loading/unloading systems).
- Rectangular clusters represent bundled investments (e.g., complete robotic cells or integrated production lines), which may require decomposition into affordable phases.

This visualization enables SME managers to strategically position candidate automation elements within their real-world financial context, identifying the most efficient investment trajectory. When a particular solution falls outside acceptable investment bounds, a *decomposition approach* may be applied–splitting the investment into sequenced stages while maintaining long-term automation goals.

This method facilitates rational planning, ensuring maximum return on investment by prioritizing modules with the highest effectiveness-to-cost ratio. It also allows enterprises to synchronize automation expansion with workforce training, infrastructure modernization, and evolving market demands.

5. Discussion

The implementation of the proposed structured methodology in a real-world SME environment demonstrated both the technical feasibility and practical relevance of workplace-level robotic automation. In contrast to traditional, top-down automation strategies that prioritize full system integration, the proposed approach enables SMEs to pursue incremental, resource-conscious automation pathways that match their operational realities.

One of the most significant findings of this study is the impact of structured parameter synthesis – not only in selecting the appropriate robotic configuration but also in aligning it with specific part families, process characteristics, and enterprise constraints. The applied method allows enterprises to move beyond intuitive or ad-hoc investment decisions and instead adopt a systematic framework for evaluating feasibility, effectiveness, and economic sustainability.

The results showed that, through careful analysis of part geometries, material properties, and auxiliary operations, it is possible to design highly adaptable robotic systems using commercially available components. The final configuration – based on a 6-axis FANUC manipulator, high-speed spindle, and dual vacuum tables – successfully reduced auxiliary processing time by up to 50% while increasing the share of productive (cutting) time to over 60%.

Importantly, the study revealed that automation at the workplace level is both achievable and impactful for SMEs. This level is often overlooked in classical automation models, yet it serves as a strategic point for initiating transformation with minimal disruption. It supports flexibility, modular implementation, and scalability – all of which are critical under conditions of uncertain demand, irregular batch sizes, and limited staff availability.

The inclusion of an investment-efficiency model further strengthens the methodology by providing a tool for prioritizing automation components based on cost-benefit analysis. In an economic context marked by reconstruction, resource scarcity, and shifting industrial demands – particularly in post-war Ukraine – such a model can support evidence-based decision-making and improve investment outcomes.

In addition to the immediate performance improvements, the modular structure of the implemented system offers a clear path for future upgrades, including the integration of artificial intelligence. AI-based tools can enhance the system’s capability to:

- automatically classify part types and select toolpaths,
- predict process parameters based on real-time data,
- optimize scheduling and part nesting,
- monitor tool wear and suggest preventive maintenance.

While AI was not integrated into the current prototype, the methodology is designed to accommodate such extensions, making it future-proof and adaptive to evolving technologies.

Moreover, due to its modular structure and phase-based decision logic, the methodology can be generalized for a wide range of SME manufacturing environments, including those with different part families, materials, or automation readiness.

Finally, the study underscores that digital transformation of SME manufacturing is not only a technological challenge but also a strategic one. Success depends on aligning technical capabilities with financial feasibility, workforce readiness, and long-term business goals. The proposed structured methodology helps bridge this gap by transforming complex automation decisions into transparent, traceable, and practically executable steps.

6. Conclusions

This study introduced and validated a structured methodology for synthesizing the parameters and architectural design of robotic technological systems, specifically tailored to the needs of small and medium-sized enterprises (SMEs) operating in the engineering sector. The approach was developed to address the unique challenges faced by SMEs, such as limited financial and human resources, constrained physical space, and the need for flexible, low-volume production capabilities.

The key findings of the study are as follows:

1. Workplace-level automation, often excluded from traditional automation hierarchies, represents a critical entry point for SMEs seeking to initiate digital transformation. Its modular nature enables cost-effective,

incremental implementation without disrupting core operations.

2. The proposed multi-stage methodology – encompassing production analysis, object profiling, process mapping, and investment prioritization – allowed for the informed selection of automation components aligned with specific production constraints and business goals.

3. Application of the methodology in a real-world case resulted in the development of a flexible robotic machining system that:

- Reduced auxiliary process time by up to 50%;
- Improved part quality and process consistency;
- Freed highly skilled personnel from repetitive operations;
- Enabled parallel part preparation and processing via dual-table layout.

4. The inclusion of an investment–effectiveness model enhanced decision-making by enabling enterprise managers to visualize and sequence automation steps based on return potential, technical complexity, and enterprise readiness. This is especially valuable in post-crisis and high-uncertainty economic environments.

5. Although AI technologies were not integrated into the current implementation, the proposed system architecture and methodology are designed to support future AI-based enhancements, including predictive maintenance, adaptive control, and automated layout synthesis.

In summary, the methodology offers SMEs a practical and scalable pathway toward robotic automation that balances technological ambition with economic realism. It enables data-driven, modular modernization of production systems and supports long-term adaptability in line with Industry 4.0 principles.

Acknowledgements

The general methodology, sequence, principles for considering parameters, and forming requirements for an automated system were used to assess the possibility and feasibility of automating the machining section at the UBC Promo enterprise. As a result of the work, recommendations were developed on the possibility and feasibility of site automation, which were partially implemented, and their implementation will continue as the enterprise develops.

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