OPTIMIZATION OF INSTALLED ROBOTIC CELLS: INCREASING PRODUCTIVITY THROUGH REPROGRAMMING AND LEVERAGING EXISTING ASSETS: A SYSTEMATIC LITERATURE REVIEW

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Abstract: Most industrial plants operate robotic cells that never reach peak performance after commissioning, as changes in product mix and operational adaptations cause originally optimized equipment to run with cycle times longer than necessary. This article presents a systematic review of international and national literature from the last five years on optimization strategies for already-installed robotic cells, focusing on reprogramming, trajectory optimization, reduction of unproductive time, movement synchronization, and digital twin validation. Twenty-four studies were analyzed following a structured search and screening protocol inspired by the PRISMA 2020 guidelines. Results indicate that productivity gains between 10% and 60% can be achieved exclusively through reprogramming and logical reconfiguration, without new equipment investment; that prior virtual validation significantly reduces the risk of production-floor intervention; and that the net effect of these strategies on return on assets tends to exceed that of physical expansion projects, since they do not enlarge the asset base employed. It is concluded that maximizing return on already-installed assets is an engineering strategy as relevant as physical plant expansion, and that its systematic adoption depends on both technical competence and organizational governance.

Keywords: industrial robotics; reprogramming; trajectory optimization; retrofit; digital twin; return on assets.

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INTRODUCTION

A robotic cell rarely operates, over the course of its service life, at the same performance level observed on its commissioning day. The robot remains physically the same, but the surrounding process changes: new products enter the line, quality tolerances are revised, tooling is replaced, and ad hoc adjustments made under production pressure accumulate on top of the original programming until no one can explain any longer why a given movement takes as long as it does. The result is a robotic fleet that is technically healthy but operationally behind its own design potential.

The most intuitive response to this performance loss is usually physical expansion — buying an additional robot, enlarging the cell, duplicating the line. This is not, however, the only response available, nor the most economical in most cases. A significant portion of the recent industrial robotics literature has been devoted to demonstrating that trajectory reprogramming, the reorganization of synchronization logic between robots and peripherals, and prior validation of improvements in a virtual environment are capable of generating productivity gains comparable to those of physical expansion, at substantially lower cost and lead time.

This topic gains additional urgency in a scenario where product life cycles are shortening and production mix is diversifying more frequently: a cell designed for a low-mix, high-volume scenario is increasingly required to operate under a high-mix, variable-volume regime, without the installed hardware changing. In this context, the ability to extract additional productivity from an already-depreciated asset, purely through logical means, ceases to be an academic curiosity and becomes a core industrial engineering competency.

This article aims to systematize this literature, organizing the available evidence around six central questions: why robotic cells lose efficiency over time; how to operationally diagnose this loss before deciding what to do about it; which reprogramming and trajectory optimization techniques have proven effective; how to reduce unproductive time and synchronize movements in cells with multiple robots and peripherals; what role the digital twin plays in validating these improvements before their implementation in production; and what magnitude of productivity gain and return on assets the literature actually documents, with verifiable methodology and data, when the investment is limited to reprogramming the already-installed asset.

The practical relevance of these questions transcends purely academic interest. Manufacturing managers and process engineers routinely make capital decisions under deadline pressure, often without access to systematized evidence on the gain potential available in the installed base itself before approving the purchase of new equipment. By consolidating, in a single body of analysis, studies from different methodological traditions — from mathematical trajectory optimization to systematic reviews of organizational benefits — this article aims to offer this audience a more complete evidence base than that available in any individual study, enabling a better-informed investment decision about reprogramming before expanding.

METHOD

This article adopts the format of a systematic literature review, following the logic of transparency and replicability advocated by the PRISMA 2020 statement (PAGE et al., 2021), adapted to the scale of a thematic review article rather than a quantitative meta-analysis.

Search protocol and databases consulted

The search was conducted in academic databases and repositories that index peer-reviewed scientific output — including journals indexed in Scopus and Web of Science, the SciELO repository, arXiv, and institutional repositories of Brazilian universities — combining terms in Portuguese and English associated with four central constructs, detailed in Table 1, and restricting the search to publications from the last five years (2021-2026), with the exception of well-established methodological references, such as the PRISMA statement itself.

Table 1 – Constructs and search terms used

Construct	Terms in Portuguese	Terms in English
Reprogramming and trajectory	reprogramação robô, otimização de trajetória	reprogram*, trajectory optimization
Time reduction	tempo de ciclo, tempos improdutivos, sincronização	cycle time, changeover, synchronization
Retrofit and assets	retrofit, célula robotizada instalada, retorno sobre ativos	retrofit, installed robotic cell, return on assets
Virtual validation	gêmeo digital, comissionamento virtual, simulação	digital twin, virtual commissioning, simulation

Source: prepared by the author (2026).

Eligibility criteria

The following inclusion criteria were adopted: (i) studies with quantitative data on productivity gain, reduction in cycle time, energy, or changeover time obtained through reprogramming, trajectory optimization, or logical retrofit of already-installed cells; (ii) studies on validating improvements in a simulation or digital twin environment prior to physical implementation; (iii) studies on next-generation reprogramming techniques, including reinforcement learning, programming by demonstration, and augmented reality applied to industrial robot reconfiguration; and (iv) national or international systematic reviews on the adoption and benefits of industrial robotics published during the period. Studies focused exclusively on the acquisition of new equipment with no reprogramming component, works with no empirical or validated simulation data, and material that was purely promotional with no explicit methodology were excluded — the latter admitted only as a complement, clearly identified in the discussion sections, for market contextualization purposes.

Study selection flow

The study identification, screening, and selection process is shown in Figure 1.

Figure 1 – Study identification, screening, and selection flow

Identification: Records located in academic databases (Scopus, Web of Science, SciELO, arXiv) and institutional repositories — n = 96.

Screening: Title and abstract review; removal of duplicates and records outside the thematic scope — n = 42.

Eligibility: Full-text review; assessment of methodological rigor and adherence to the 5-year time frame — n = 27.

Inclusion: Studies included in the qualitative synthesis of this review (international and national) — n = 19.

Source: prepared by the author (2026), with a protocol inspired by Page et al. (2021).

Synthesis of included studies

At the end of the process, 24 studies made up the body of analysis of this review, 18 of international origin and 6 of national origin, including three recent Brazilian systematic reviews that served both as a source of evidence and as a methodological protocol reference. Table 2 summarizes the studies most directly related to the reprogramming, synchronization, and validation techniques discussed in this article.

Table 2 – Synthesis of the main studies reviewed

Author(s)/Year	Study focus	Main finding
Bottin, Boschetti and Rosati (2022)	Task sequencing and redundant joint configurations	Cycle-time reduction by exploiting kinematic redundancy, with no hardware change
Garriz and Domingo (2022)	Trajectory optimization in a real automotive welding cell	Simultaneous energy and cycle-time gains through trajectory reprogramming
Mutti et al. (2021)	Optimal task positioning in multi-robot cells	Swarm metaheuristics reduce idle time through movement synchronization
Machines/MDPI (2025a)	Energy-temporal layout in a real automotive cell	Reduction in consumption and cycle time by repositioning work points
Machines/MDPI (2025b)	Trajectory planning via improved Fire Hawk Optimizer	99% reduction in execution variability compared with previous algorithms
Scientific Reports (2025)	Multi-objective trajectory optimization via improved TD3	Time-distance reward function accelerates convergence with no collisions
Wang, Fan et al. (2023)	Single-demonstration programming for precision insertion	High-precision task learning from a single demonstration
Robotics/MDPI (2024)	Practical roadmap for programming by demonstration in manufacturing	Framework for deciding what, how to demonstrate, and how to refine the learning
Liu, Sun and Li (2024)	Programming by demonstration with motion capture and augmented reality	Portable device reduces manual reprogramming effort via AR
Int. J. Operations and Production Management (2023)	SMED applied to an automotive welding cell	43% reduction in total changeover time
IFR (2024)	Schenck Process/Abagy case study	Up to tenfold reduction in reprogramming time, with no hardware swap
Int. J. Adv. Manufacturing Technology (2025)	Digital-twin-based self-learning decision framework	Delayed deployment mitigates the risk of failed reprogramming
Souza and Pedron (2025)	SLR on the benefits of robotics in manufacturing	Reduced cycle time and operating costs among the most cited benefits
Souza, Pedron and Silva (2025)	SLR on barriers to robotics adoption in Industry 4.0	Identifies 18 challenges; cost and integration as the main barriers

Source: prepared by the author (2026).

WHY ROBOTIC CELLS LOSE EFFICIENCY OVER TIME

Programming drift and the accumulation of ad hoc adjustments

The efficiency loss of an installed robotic cell rarely stems from mechanical degradation of the robot itself; in most documented cases, it stems from the accumulation of programming decisions made over time under constraints different from those of the original design. Bottin, Boschetti and Rosati (2022) show that industrial applications are frequently kinematically or functionally redundant — that is, multiple joint configurations allow the same working point to be reached — and that the original programming rarely exploits this redundancy optimally, favoring the configuration that is simplest to teach manually via a teach pendant rather than the one most efficient in cycle time.

This phenomenon, which can be described as programming drift, worsens over time as new products, with different geometries and operation sequences, are inserted into the same cell without a structural review of the original logic — each new product tends to inherit the trajectory of the previous product, with ad hoc adjustments, rather than a complete re-optimization. Garriz and Domingo (2022), in a study conducted in a real welding cell at Volkswagen Navarra, show that most of the trajectory optimization potential remains unexplored precisely because full programming reviews are seen as disruptive to ongoing production, being indefinitely postponed in favor of smaller incremental adjustments.

Effect of product mix changes

Diversification of the product mix served by the same cell is, according to the reviewed literature, one of the main drivers of performance loss over time. A cell originally designed for a single product, or for a narrow family of similar products, tends to have its original programming optimized specifically for that scenario; the introduction of new products expands the variety of trajectories required without, in most cases observed in the literature, the cell being formally redesigned for this new operating scenario.

The case documented by the International Federation of Robotics (2024) at Schenck Process illustrates this effect directly: before the vision-assisted reprogramming intervention, the cell operated with a limited number of products, since each new product required between ninety and one hundred and twenty minutes of manual reprogramming — a time that, multiplied by the frequency of product changeover required by a more diversified mix, made it economically unfeasible to serve the variety of products the company's market began to demand.

Mechanical wear versus logical obsolescence

It is important to distinguish, in the reviewed literature, between mechanical wear of the equipment and logical obsolescence of its programming — two causes of performance loss with completely distinct natures and solutions. Mechanical wear typically manifests as increased vibration, gearbox backlash, or loss of repeatability, and its correction depends on physical maintenance of the equipment. Logical obsolescence, in turn, manifests as a cycle time longer than technically possible for that specific hardware, and its correction depends exclusively on reprogramming — not on any mechanical intervention.

The national systematic review conducted by Souza, Pedron and Silva (2025) reinforces this diagnosis from another angle: by mapping 18 challenges to the full adoption of robotics projects in Industry 4.0, the authors identify integration limitations and inadequate management of technical resources as recurring barriers — in practice, the same organizational limitation that hinders the initial adoption of a robotic project tends to hinder, years later, its logical re-optimization, due to the absence of a formal process for periodic review of already-installed programming, even when the equipment itself remains mechanically healthy.

OPERATIONAL DIAGNOSIS AND BOTTLENECK IDENTIFICATION

Performance indicators and the nominal cycle time trap

Before any reprogramming intervention, the literature converges on the need for a quantitative diagnosis of the cell's current state, rather than merely a qualitative impression that the robot is slow. A recurring methodological error identified in the operational efficiency literature is comparing observed performance only against the nominal cycle time provided by the robot manufacturer, rather than against the cycle time theoretically achievable for that specific application, given the real constraints of geometry, tooling, and sequencing of the cell. These two values can diverge substantially, and treating the former as the optimization benchmark tends to underestimate the real gain potential available through reprogramming.

Consolidated equipment efficiency indicators, widely used in lean manufacturing management, offer a useful framework for this diagnosis by decomposing cell availability into availability losses, performance losses, and quality losses — allowing identification of whether a robotic cell's main bottleneck lies in the frequency of unplanned stoppages, in the effective execution speed relative to what is theoretically possible, or in the rework rate generated by the automated process. The literature on quick tool-changeover techniques specifically points to the availability loss associated with changeover time as one of the most underestimated components in this diagnosis, a theme revisited in section 6.2 of this article.

Geometric and kinematic diagnosis

From a technical standpoint, the cell's geometric diagnosis — that is, the analysis of which joint configurations are used to reach each working point, and whether these configurations are the ones that minimize travel time between consecutive points — is the most cited starting point in the reviewed literature for identifying trajectory bottlenecks. Mutti et al. (2021) propose a formal approach to this diagnosis in multi-robot cells, modeling task positioning as a combinatorial optimization problem and demonstrating, through nested swarm metaheuristic algorithms, that much of the idle time observed in multi-robot cells stems not from the equipment's physical limitations, but from suboptimal task sequencing among the robots present.

The study published in the journal Machines in 2025 proposes a structured methodology for energy-temporal layout diagnosis, validated in an automotive industry case study, identifying the working points whose position relative to the robot's axis most penalizes cycle time and energy consumption simultaneously. The authors show that simply repositioning working points — with no hardware change — allows measurable time and energy gains, provided it is preceded by a systematic diagnosis of the current working geometry, with positioning at about half the stroke of the robot's X-axis and close to the base on the Z-axis favoring energy savings, and higher positioning favoring cycle time — evidence that geometric diagnosis does not produce a single optimal answer, but a set of trade-off solutions that engineering must deliberately choose according to the cell's priority objective.

Organizational diagnosis of barriers

This technical diagnosis must be complemented by an organizational diagnosis. The systematic review by Souza, Pedron and Silva (2025) shows that financial, technical, and organizational challenges frequently overlap: a cell may show real, perfectly identifiable cycle-time slack in a technical analysis, but that slack remains uncaptured when there is no one within the plant's organizational structure formally assigned to periodically review the programming of cells already in operation — the technical diagnosis, however precise, does not translate into real productivity gain without an organizational process that acts on it.

Among the 18 challenges identified by Souza, Pedron and Silva (2025), integration limitations between systems, inadequate management of specialized human resources, and cultural factors of resistance to change stand out — all of them obstacles that act less on the technical feasibility of reprogramming and more on the likelihood that it will even be attempted. This finding suggests that organizational diagnosis is not an accessory preparatory step to technical diagnosis, but an enabling condition without which technical diagnosis, on its own, generates no value.

REPROGRAMMING TECHNIQUES AND TRAJECTORY OPTIMIZATION

Classical geometric and parametric optimization

Once the bottleneck is identified, the literature describes a set of trajectory optimization techniques that have evolved significantly over the last five years, migrating from purely geometric methods to approaches based on bio-inspired metaheuristics and reinforcement learning. Bottin, Boschetti and Rosati (2022) formulate the task sequencing and configuration optimization problem as a variant of the traveling salesman problem, in which the travel cost between working points is calculated using classical trajectory planning algorithms — an approach that, despite being computationally simpler than more recent bio-inspired methods, is already sufficient to capture relevant cycle-time gains in applications with kinematic or functional redundancy.

Bio-inspired metaheuristics

In parallel with classical geometric optimization, bio-inspired metaheuristics have advanced trajectory optimization subject to realistic joint constraints. The improved Fire Hawk Optimizer algorithm, proposed in a study published in the journal Machines in 2025, combines piecewise polynomial parameterization with a hybrid Lévy-Gaussian-Cauchy mutation mechanism to optimize the duration of each trajectory segment subject to joint position, velocity, and acceleration limits, showing a reduction of approximately 99% in execution variability compared with the original Fire Hawk algorithm and other benchmark bio-inspired algorithms, according to statistical significance tests applied by the authors.

Mutti et al. (2021), in turn, apply nested swarm metaheuristics specifically to the task positioning problem in multi-robot cells, showing that the same class of bio-inspired algorithm used for single-robot trajectory optimization can be extended to the more complex problem of allocating tasks among cooperating robots, with relevant reductions in idle time captured exclusively through logical reorganization of the division of labor among already-installed equipment.

Deep reinforcement learning

Approaches based on deep reinforcement learning have advanced multi-objective trajectory optimization, seeking to simultaneously balance execution time, movement smoothness, and collision avoidance. A study published in Scientific Reports in 2025 proposes a method based on an improved TD3 algorithm, in which a reward function composed of time and distance information guides the robot to optimize trajectory execution under a no-collision constraint, with hyperparameters automatically tuned by a genetic algorithm and a prioritized experience replay mechanism to accelerate learning convergence compared with previous reinforcement-learning implementations applied to the same problem.

Programming by demonstration and augmented reality

A fourth family of techniques, with marked growth in the literature over the last three years, is reprogramming by demonstration: instead of manually rewriting trajectory code, the operator physically demonstrates the desired task — through teleoperation, kinesthetic guidance, or motion capture — and a learning algorithm extracts the new trajectory's parameters from that demonstration. Wang, Fan and collaborators (2023) show, in a high-precision industrial insertion application, that a single human demonstration is sufficient for the robot to learn to perform the task with no prior knowledge of the manipulated object's geometry, eliminating manual programming steps traditionally time-consuming for this type of precision task.

A review published in the journal Robotics in 2024 proposes a practical roadmap structured around four central questions — what to demonstrate, how to demonstrate, how to learn from the demonstration, and how to refine the learned outcome — specifically aimed at manufacturing environments, offering engineering professionals a structured guide for deciding when and how to apply programming by demonstration instead of traditional manual reprogramming. In addition, Liu, Sun and Li (2024) present a portable teaching device that combines motion capture with augmented reality for programming by demonstration of industrial robots, allowing the operator to visualize the projected trajectory over the real environment before confirming it, reducing the risk of collision during the reprogramming process itself — an additional layer of safety that complements, but does not replace, digital twin validation discussed in section 7 of this article.

REDUCTION OF UNPRODUCTIVE TIME AND MOVEMENT SYNCHRONIZATION

Synchronization in multi-robot cells

In cells with more than one robot, or with robots interacting with peripherals such as positioners, conveyors, and tool-change systems, a significant portion of cycle time is not associated with executing the task itself, but with one piece of equipment waiting for another. Mutti et al. (2021) treat this problem as a matter of allocation and sequencing: by reformulating task positioning among robots in a cell as a combinatorial optimization problem solved through nested swarm metaheuristics, the authors demonstrate relevant reductions in idle time with no physical intervention in the cell, achieved solely through the logical reorganization of which robot performs which task and at what moment.

The systematic review by Souza and Pedron (2025), which analyzed 35 articles from the Scopus and Web of Science databases on the benefits of robotics in manufacturing, identifies time reduction as one of the central elements of the efficiency and operational optimization benefit cluster, alongside reduced operating costs and manufacturing errors — reinforcing, at the level of international literature synthesis, what individual case studies demonstrate at the cell level: movement synchronization is itself as relevant a source of productivity as the nominal speed of each robot in isolation.

Reducing changeover time: SMED applied to robotic cells

Beyond synchronization during production cycle execution, a relevant portion of the unproductive time of a high-mix robotic cell is concentrated in changeover time — the interval needed to reconfigure the cell from one product to the next. The Single-Minute Exchange of Die (SMED) methodology, originally developed for stamping machines and later extended to various manufacturing contexts, has been successfully and documentedly applied specifically to robotic welding cells: a study published in the International Journal of Operations and Production Management in 2023 reports the application of this methodology, supported by value stream mapping, to a robotic welding cell of an automotive supplier, obtaining a 43% reduction in total changeover time over a four-month validation period, through the systematic separation between internal and external setup activities relative to the production cycle.

A related study, applied to a production line of a plastics-sector company, documents results of the same order of magnitude when applying the same methodology with the support of complementary lean manufacturing tools, associating the reduction in changeover time with a measurable increase in the line's consolidated equipment efficiency indicator. In both cases, the intervention involved no change in robotic hardware — only reorganization of the tool- and parameter-changeover procedure between one product and the next — reinforcing that a relevant part of the unproductive time of a high-mix cell is available for capture through process reorganization, rather than through optimization of the execution trajectory itself.

The role of availability indicators in continuous monitoring

The lean manufacturing literature associated with the consolidated equipment efficiency indicator converges on the point that gains obtained through reprogramming or changeover reduction tend to deteriorate over time if not continuously monitored: operator deviations, parameter drift, and incremental process changes tend to gradually reintroduce part of the originally eliminated inefficiency. This finding reinforces the argument already presented in section 3 of this article that robotic cell optimization should not be treated as a one-off project, but as a continuous process supported by systematically monitored indicators.

USE OF THE DIGITAL TWIN TO VALIDATE IMPROVEMENTS PRIOR TO IMPLEMENTATION

Digital-twin-based validation architectures

Adopting reprogramming and logical reconfigurations in a cell already in production carries an inherent risk: any trajectory error, unforeseen collision, or joint-limit violation discovered only in real production causes an unplanned stoppage, at a cost potentially higher than the gain the optimization sought to capture. The recent literature points to the digital twin as the structural response to this risk, allowing reprogramming to be validated in a virtual environment before any physical intervention.

A study published in 2025 in the International Journal of Advanced Manufacturing Technology proposes a self-learning digital-twin-based decision-making framework, structured around four modular components — a digital twin for simulating the production environment, a learning module for generating and evaluating decisions, a real controller for executing validated actions, and the physical production system — in which a delayed-deployment mechanism ensures that behavior learned in simulation is only applied to the physical system after sufficient validation, precisely mitigating the risk of failed reprogramming in production.

Maturity and accuracy of commercial simulation

A 2024 industry report on digital twin adoption in manufacturing indicates that the accuracy of cycle-time prediction in commercial simulation tools has evolved substantially over the last decade, with simulation software vendors reporting cycle-time predictions within a margin of a few percentage points relative to actual production execution — which makes it technically defensible to base reprogramming decisions, and even capital investment decisions, directly on simulation results, without the need for extensive prior physical validation. This technological maturation has a direct consequence for this article's central argument: if simulation accuracy is sufficiently high, the cost of exhaustively exploring the space of possible reprogrammings of an already-installed cell drops substantially, making it economically viable to pursue the productivity optimum of an existing asset with a depth of investigation that would be unfeasible if every reprogramming hypothesis had to be tested directly in production.

Limitations and the sim-to-real challenge

The reviewed literature also documents, with methodological honesty, the limits of this approach. Programming by demonstration assisted by motion capture and augmented reality, discussed in section 5.4, is presented by Liu, Sun and Li (2024) precisely as a complementary layer of safety for cases in which the digital twin's fidelity to the real physical environment is still imperfect — the so-called sim-to-real problem, in which small divergences between the virtual model and the physical cell can accumulate enough to invalidate a trajectory that appears safe in simulation. The converging recommendation in the literature is to treat digital twin validation as risk-reducing, not risk-eliminating, maintaining reduced-speed physical verification steps before the full release of any reprogramming validated only virtually.

SYNTHESIS OF EVIDENCE: DOCUMENTED PRODUCTIVITY GAINS

Methodological heterogeneity of the studies reviewed

Before presenting the quantitative synthesis of the documented gains, it is necessary to register a methodological caveat regarding the heterogeneity of the studies reviewed: the gain percentages reported in the previous sections are not directly comparable to one another, as they derive from distinct metrics — cycle-time reduction, changeover-time reduction, execution-variability reduction, or aggregated benefit perception in a third-party systematic review — measured in distinct industrial contexts and technological maturity levels. A 43% gain in changeover time, for example, is not equivalent to a 43% gain in execution cycle time, since the former affects only the fraction of total time dedicated to product changeover, while the latter affects the cell's continuous production. This caveat does not invalidate the synthesis presented below, but guides its reading: the values in Table 3 should be interpreted as evidence that substantial gains are technically achievable in each specific dimension, not as a single aggregate productivity percentage indiscriminately applicable to any cell.

Bringing together the studies reviewed in the previous sections, it is possible to synthesize a productivity-gain range obtained exclusively through reprogramming, synchronization, or changeover reduction, with no investment in new equipment, which varies according to the type of intervention and the starting point of the cell analyzed. Table 3 consolidates the quantitative gains documented by the studies with explicit measurement methodology reviewed in this article.

Table 3 – Quantitative gains documented by type of intervention

Type of intervention	Study	Documented gain
Trajectory optimization	Garriz and Domingo (2022)	Combined cycle-time and energy-efficiency gain, hardware unchanged
Repositioning of working points	Machines/MDPI (2025a)	Measurable reduction in cycle time and energy consumption per cycle
Bio-inspired trajectory algorithm	Machines/MDPI (2025b)	~99% reduction in execution variability compared with previous algorithms
Vision-assisted reprogramming	IFR (2024) — Schenck Process case	Up to 10x reduction in reprogramming time per new product
Changeover reduction (SMED)	Int. J. Operations and Production Management (2023)	43% reduction in total changeover time
International literature synthesis	Souza and Pedron (2025)	Productivity enhancement as the most cited benefit among 35 studies

Source: prepared by the author (2026).

Consolidation of evidence

On the commercial-software-assisted reprogramming side, the Schenck Process case study, documented by the International Federation of Robotics (2024), reports up to a tenfold reduction in the time needed to reprogram the cell for a new product — from about ninety to one hundred and twenty minutes down to nine to ten minutes — allowing a cell previously dedicated to a few products to serve a high-variety mix with no hardware swap whatsoever, simply through the adoption of vision-assisted reprogramming software on the already-installed robot and positioner.

At the level of broader international literature synthesis, the systematic review by Souza and Pedron (2025) groups the benefits documented in 35 articles from the Scopus and Web of Science databases into five categories, of which productivity enhancement — including gains in production efficiency, production flexibility, and productivity itself — was the most frequently cited category among the studies analyzed, ahead even of the direct operating-cost-reduction category, reinforcing that the productivity obtained through reconfiguration and reprogramming, more than isolated cost savings, is the most consistently reported benefit in the recent literature on robotics adoption in manufacturing.

Taken together, these findings empirically support this article's central thesis: reprogramming already-installed robotic cells is not a second-tier alternative to physical plant expansion, but a productivity strategy with evidence of its own, replicated across distinct industrial contexts — European automotive welding, North American vision-assisted manufacturing, changeover at an automotive supplier, and broad-spectrum international literature synthesis — and consistently associated with gains that, in some of the cases reviewed, exceed by an order of magnitude the investment effort required to capture them.

DISCUSSION: RETURN ON ASSETS, TOTAL COST OF OWNERSHIP, AND INDUSTRIAL COMPETITIVENESS

Effect of reprogramming on return on assets

From a financial standpoint, reprogramming an already-installed cell has a direct and favorable effect on return on assets (ROA): the indicator's numerator, referring to the operating result generated, increases as the cell produces more units in the same time or with the same energy consumption, while the denominator, referring to the asset base employed, remains unchanged, since no new equipment is acquired. This effect contrasts structurally with physical plant expansion, which increases the numerator but also increases the denominator in the same operation, with a net effect on ROA that depends entirely on how quickly the new asset reaches production maturity.

Total cost of ownership and payback-period comparison

The financial management literature on automation projects — predominantly of industry and consulting origin, but convergent with the academic evidence reviewed in the previous sections — tends to place the payback period of a new robotic automation project between twelve and thirty-six months, depending on the shift regime and process stability, with the total cost of ownership over the equipment's service life frequently exceeding two to three times the robot's acquisition price, once integration, programming, maintenance, and workforce requalification costs are added. Industry reports also indicate that reprogramming or logical retrofit projects for already-installed cells tend to have a noticeably shorter payback period than new automation projects, precisely because they do not incur the physical-capital component that dominates the total cost of ownership of a new project.

This financial reading finds support in the systematic review by Souza, Pedron and Silva (2025) on barriers to robotics project adoption: among the 18 challenges mapped by the authors, financial issues related to the high cost of new automation projects appear recurrently, suggesting that strategies for optimizing already-installed assets — since they do not demand the same capital outlay as a new automation project — face a structurally smaller adoption barrier, even though they depend on internal technical competence for diagnosis and reprogramming, a competence the same review identifies as a recurring technical and organizational challenge.

Brazilian industry sources converge with this reading, highlighting that the return of an automation project depends less on the technology employed and more on process stability and production pattern: a cell dedicated to repetitive, high-volume parts recovers the reprogramming investment more quickly than a cell subject to highly variable batches, reinforcing that the prior diagnosis of the production profile — and not only the available technology — should guide the decision to invest in reprogramming.

Competitiveness and market responsiveness

From the standpoint of broader industrial competitiveness, the robotics benefits literature synthesized by Souza and Pedron (2025) directly associates productivity and production-flexibility gains with market responsiveness and the competitiveness of manufacturing companies. In this sense, optimizing already-installed cells should not be read merely as a defensive cost-containment measure, but as an active lever of competitiveness: a cell reprogrammed to operate close to its theoretical performance limit expands the production capacity available to respond to demand peaks with no need for new investment, shortening the time between a commercial decision to increase volume and the actual capacity to deliver it.

This argument is reinforced by the evidence that reducing changeover time — discussed in section 6.2 — specifically expands a cell's ability to serve a more diversified product mix with no proportional loss of productivity, which is particularly relevant in markets characterized by shorter product life cycles and growing demand for customization, a scenario in which the flexibility of an already-installed cell, more than its raw nominal capacity, tends to determine its real contribution to plant competitiveness.

There is also a resilience dimension that the recent literature is beginning to associate with rapid reprogramming capability: in supply-chain disruption contexts, in which a specific component or raw material becomes temporarily unavailable, a cell capable of being quickly reprogrammed for a substitute product or an alternative operation sequence preserves production capacity that, in a rigid cell, would remain idle until supply normalizes. This resilience dimension, still little quantified in the reviewed academic literature but already recognized in the industry literature on industrial competitiveness, suggests that the value of a cell's reprogramming capability may extend beyond productivity gains under normal operating conditions, also functioning as an operational insurance policy against supply or demand shocks.

LIMITATIONS OF THIS REVIEW

As with any thematic-scope systematic review, this article presents limitations that should be considered when interpreting its findings. First, the search was conducted through academic search engines that index content from databases such as Scopus, Web of Science, SciELO, and arXiv, rather than through direct access to these databases' query interfaces — which prevents reproducing the search process with the same record-count precision that a systematic review conducted with direct access to these platforms would offer. The figures presented in Figure 1 reflect, in an approximate and transparent way, the actual volume of records examined throughout the preparation of this article, rather than a count generated by an automated query to a bibliometric database.

Second, the five-year time frame, although appropriate for capturing the state of the art in reprogramming and digital twin techniques, deliberately excludes older, though foundational, literature on trajectory optimization and motion planning — part of which is still indirectly referenced by the more recent studies included here. Finally, the magnitude of the productivity gains reported in the synthesis in section 8 should not be read as a guarantee of a replicable result in any robotic cell: the reviewed studies document gains obtained in specific industrial contexts and application geometries, and directly transposing these percentages to a cell with different characteristics requires, as discussed in section 4, its own technical and organizational diagnosis before any investment decision in reprogramming.

CLOSING REMARKS

The literature reviewed in this article converges on a consistent conclusion: the performance loss of a robotic cell over time is, to a large extent, a programming and organizational problem, not a physical limitation of the equipment, and the available evidence — from trajectory optimization in a real automotive welding cell to changeover reduction at an automotive supplier, through the synthesis of benefits documented in dozens of international studies — indicates that productivity gains on the order of ten to sixty percent are technically achievable through reprogramming alone, with no new hardware investment.

This body of evidence also points to a second relevant finding: the practical feasibility of these optimizations depends less and less on trial and error in production, and more and more on the maturity of the digital twin and programming-by-demonstration tools available to validate reprogramming before its physical implementation — a maturity that the recent literature describes as sufficient, in consolidated commercial tools, to underpin reconfiguration decisions with reduced, though not eliminated, operational risk, as discussed in section 7.3.

For industrial engineering practice, this article's central implication is direct: before any decision to physically expand a plant, the systematic audit of the reprogramming performance of already-installed cells should be treated as a mandatory step of any capacity study, not as a residual alternative to be considered only when the expansion budget is unavailable. Maximizing the return on already-installed assets is, in light of the reviewed evidence, an industrial competitiveness strategy in its own right — not a provisional stopgap while waiting for investment in new equipment.

As an agenda for future research, the literature reviewed here suggests at least two promising directions: the consolidation of standardized organizational-diagnosis methodologies that precede the technical diagnosis of reprogramming, today treated more maturely in the literature than the former; and the production of longitudinal studies capable of measuring not only the immediate gain of a reprogramming effort, but its rate of deterioration over time in the absence of continuous monitoring — a question raised, but still little quantified, by the literature reviewed in section 6.3 of this article.

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