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Process Integration and Industrial Automation in Chemical Plants: Impacts on Productivity

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Summary

This article analyzes **process integration and industrial automation in chemical plants.** as determining factors for increasing productivity and competitiveness in an increasingly challenging global market. The research discusses the use of emerging technologies such as **digital twins, the Internet of Things (IoT) ,** and **advanced control systems,** evaluating how these resources can be applied to optimize operations, reduce costs, minimize failures, and increase production sustainability. The literature shows that, in a sector characterized by high technical complexity and regulatory rigor, the integration of automation and chemical processes is crucial to maintaining quality, safety, and efficiency standards. Furthermore, practical cases are presented that demonstrate productivity gains when industries adopt digital solutions and predictive monitoring systems. The article argues that the future of chemical engineering depends on the consolidation of strategies that combine science, technology, and management, creating smart chemical plants capable of responding in real time to market demands and sustainability pressures.

Keywords: Industrial automation; Process integration; Chemical plants; Digital twins; Productivity.

Abstract

This article analyzes **process integration and industrial automation in chemical plants** as determining factors for increasing productivity and competitiveness in an increasingly challenging global market. The study discusses the use of emerging technologies such as **digital twins, Internet of Things (IoT),** and **advanced control systems,** assessing how these resources can be applied to optimize operations, reduce costs, minimize failures, and enhance productive sustainability. Literature indicates that in a sector characterized by high technical complexity and strict regulation, the integration between automation and chemical processes is crucial to maintaining standards of quality, safety, and efficiency. Furthermore, practical cases are presented that highlight productivity gains when industries adopt digital solutions and predictive monitoring systems. The article argues that the future of chemical engineering depends on consolidating strategies that combine science, technology, and management,

creating smart chemical plants capable of responding in real time to market demands and sustainability pressures.

Keywords: Industrial automation; Process integration; chemical plants; Digital twins; Productivity.

1. Introduction to Process Integration and Industrial Automation

Process integration and industrial automation represent one of the most profound transformations the chemical industry has faced in recent decades. Traditionally, chemical plants operated with segmented systems, in which each stage of the production process was monitored in isolation. This fragmentation led to efficiency losses, increased operating costs, and a greater likelihood of failures. With advances in process engineering and automation, it became possible to create interconnected systems that allow for real-time monitoring and continuous optimization. According to Stephanopoulos (1993), modern process engineering only reaches its full potential when incorporated into advanced control systems capable of aligning physical, chemical, and economic variables within a single operational flow.

In the current context, marked by intense competitive pressure and increasing regulatory requirements, automation has gone from being a differentiator to an essential requirement for survival in the chemical industry. Plants that do not incorporate integration solutions risk losing competitiveness and even compromising operational safety. Studies by Luyben (2012) show that companies that invested in process automation achieved average productivity gains of 20% and reductions of up to 15% in energy costs, highlighting the transformative potential of this approach.

Another important point is that process integration is not limited to the application of technology, but involves a cultural and managerial shift. Organizations need to understand that automation is not just a control tool, but a strategic element that directly impacts governance and long-term planning. Kaplan and Mikes (2012) emphasize that operational and financial risks can only be effectively mitigated when considered within an integrated system, in which technical data and management decisions continuously feed into each other.

The digitalization of the chemical industry, also known as Industry 4.0, reinforces this movement. Technologies such as smart sensors, big data analysis, and artificial intelligence expand companies' ability to predict failures, adjust processes in real time, and make evidence-based decisions. Brynjolfsson and McAfee (2017) point out that the incorporation of intelligent automation generates not only production efficiency but also flexibility, a fundamental element in increasingly volatile markets.

Additionally, process integration promotes environmental gains, an aspect increasingly valued by regulatory agencies and consumers. Advanced control systems allow for reduced raw material waste, optimized energy consumption, and minimized emissions, aligning industrial productivity with sustainability goals. Hollnagel (2011)

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argues that resilient systems are those capable of combining efficiency and socio-environmental responsibility, which reinforces the role of automation in the future of chemical plants.

Finally, the introduction to this article positions process integration and industrial automation as **strategic pillars** for the development of chemical engineering. It's not just about incorporating new technologies, but also about transforming the operating logic of plants, making them intelligent, adaptable, and results-oriented. This shift will be discussed in the following sections, which analyze theoretical foundations, practical applications, and concrete impacts on industrial productivity.

2. Theoretical Foundation: Automation and Process Integration

The theoretical foundation for automation and process integration in chemical plants is based on three main axes: **integrated process engineering, advanced control systems ,** and **production digitalization.** The first axis, linked to process engineering, is based on the premise that production efficiency can only be achieved through overall plant optimization, not through the isolated analysis of its stages. Douglas (1988) argues that process synthesis must simultaneously consider economic, energy, and environmental factors, which is only possible through integrated mathematical models.

The second axis concerns the role of advanced control systems. Tools such as **model-based predictive control (MPC)** allow predicting future system behavior and adjusting operating variables before deviations compromise productivity. Studies by Qin and Badgwell (2003) show that the use of MPC in chemical plants results in significant gains in operational stability and reduced variability, factors directly linked to the final product quality. This integration between mathematical modeling and automation highlights the importance of ongoing dialogue between process engineers and control specialists.

The third axis involves digitalization, a phenomenon that has been called **the fourth industrial revolution** or **Industry 4.0.** Digital technologies such as IoT, digital twins, and artificial intelligence expand integration capabilities, providing real-time data and simulating operational scenarios even before they are executed. Rosen et al. (2015) emphasize that digital twins allow for the creation of accurate virtual representations of the plant, facilitating the identification of bottlenecks and the proposal of predictive solutions. This capability transforms the logic of automation from reactive to proactive.

Another relevant aspect of the theoretical framework is the link between automation and organizational resilience. According to Hollnagel (2011), resilient organizations are those capable of anticipating failures, continuously monitoring their operations, and learning from adverse events. Process integration, by providing comprehensive and accurate data, strengthens the resilience of chemical plants, ensuring they are less susceptible to disruptions and more adaptable to external changes.

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The **resource-based** theory of competitive advantage (Barney, 1991) also offers a lens for analyzing industrial automation. The ability to integrate processes and utilize advanced technology can be seen as a strategic resource, difficult to imitate and replace, which confers a sustainable advantage on companies that master it. This shows that automation is not just an operational tool, but a strategic asset.

Finally, the theoretical foundation demonstrates that industrial automation and process integration are not isolated practices, but structuring elements of a new productive logic. The convergence of chemical engineering, data science, and control systems represents the foundation on which the chemical industry of the future is built. This theoretical basis will be the starting point for the practical analysis in the following sections, which discuss real-life cases and measurable impacts on productivity.

3. Emerging Technologies in Chemical Plant Automation

The adoption of emerging technologies in chemical plant automation redefines the concept of industrial productivity. The use of the **Internet of Things (IoT),** for example, allows the installation of smart sensors at strategic points throughout the plant, collecting continuous data on temperature, pressure, flow, and chemical composition. This data is transmitted in real time to centralized platforms, enabling instant performance analysis and the identification of anomalies. Studies by Lee et al. (2015) demonstrate that IoT applied to the chemical industry can reduce unscheduled downtime by up to 25% and significantly extend equipment lifespan. This connectivity transforms the plant into a living organism, capable of responding immediately to internal and external variations.

Another technology gaining relevance is **digital twins.** This innovation creates exact virtual replicas of chemical plants, allowing for the simulation of operational scenarios, the prediction of failures, and the testing of alternatives before physical implementation. Rosen et al. (2015) argue that digital twins function as highly accurate virtual laboratories, reducing the costs of physical experimentation and increasing safety. Chemical companies that have adopted this practice report significant gains in energy efficiency and maintenance planning, as they can predict when and where wear and tear will occur.

Advanced control systems, such as the aforementioned **Model Predictive Control (MPC),** also represent important milestones in automation. Their ability to anticipate future behavior based on mathematical models allows for reduced variations and maintains processes within optimal parameters for extended periods. Qin and Badgwell (2003) highlight that the application of MPC in complex chemical processes results in annual savings ranging from 5 to 10% of the plant's total operating costs. This efficiency translates directly into greater competitiveness in the global market.

Artificial intelligence **(AI)** further expands the possibilities of automation. Machine learning algorithms analyze large volumes of data collected by the IoT and adjust parameters autonomously, learning from historical patterns and predicting failures in advance. Brynjolfsson and McAfee (2017) argue that AI applied to the chemical industry

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It not only replaces human processes but also expands decision-making capacity, making plants more adaptable and less vulnerable to external variables. The integration of AI, IoT, and digital twins creates an integrated digital ecosystem, where prevention and optimization are constant.

Another technological advance is the use of **industrial robotics** in high-risk chemical processes. Automated robots are used in harsh environments, such as high-pressure reactors or highly toxic areas, reducing worker exposure to hazardous conditions. In addition to increasing safety, robotics helps standardize critical operations, minimizing human error. According to a report by the International Federation of Robotics (2019), the adoption of robots in chemical sectors has increased 15% annually over the last decade, reinforcing their relevance for the future of the industry.

Big data analysis also plays a crucial role in automation. The enormous amount of data generated by sensors, control systems, and digital twins needs to be processed and interpreted efficiently. Big data platforms allow for the correlation of variables that were previously analyzed in isolation, revealing hidden patterns and offering strategic insights. Mayer-Schönberger and Cukier (2013) emphasize that analyzing large volumes of data redefines the way industries plan investments and respond to crises, increasing the agility and accuracy of decisions.

Therefore, the integration of emerging technologies transforms chemical plants into intelligent, connected, and autonomous systems. The convergence of IoT, digital twins, MPC, AI, robotics, and big data creates a new automation paradigm, in which productivity is no longer measured solely in terms of production volume but includes safety, sustainability, and resilience. This transformation will be crucial to meeting the challenges of the chemical industry in the 21st century.

4. International Case Studies of Automation in Chemical Plants

An analysis of international cases highlights how automation and process integration are already generating concrete impacts on industrial productivity. One of the best-known examples is BASF **in** Germany, which implemented digital twin systems on a large scale in its chemical plants. According to the company's own report (2019), adopting the technology enabled a 15% reduction in energy consumption and a 20% increase in production efficiency in certain segments. This case demonstrates that digital integration is not only viable but also highly profitable, becoming a benchmark for the sector.

In the United States, **Dow Chemical** has invested heavily in IoT and artificial intelligence. Sensors distributed throughout its plants monitor critical variables and feed machine learning algorithms, which in turn issue predictive alerts about potential failures. This strategy has reduced maintenance costs by 30% and increased operational reliability, allowing the company to stand out as one of the most innovative in the industry.

Studies by the American Chemical Society (2020) highlight Dow as an example of how technological integration transforms risk management into a competitive advantage.

Another relevant case is that of **Mitsubishi Chemical,** in Japan, which used advanced control systems (ASC) to optimize polymerization processes. Before automation, variations in final product quality were high, generating rework and waste. After implementing ASC, a 40% reduction in process variability and significant gains in product uniformity were observed. This example demonstrates how advanced control contributes not only to productivity but also to the company's quality and reputation in the global market.

In India, chemical companies in the fertilizer sector have been leveraging automation technologies to cope with the high demand for large-scale production. The combined use of IoT and big data has enabled real-time monitoring of inventories, raw material consumption, and reactor performance, reducing bottlenecks and increasing operational predictability. According to the report by the Federation of Indian Chambers of Commerce and Industry (FICCI, 2018), companies that adopted advanced automation recorded productivity gains of over 25%, which strengthened their competitive position in international markets.

In the United Kingdom, experiments with **industrial robotics** in high-risk chemical synthesis plants are also notable. Robots were employed in handling highly reactive substances, replacing human operators at critical stages. This change not only reduced workplace accidents but also increased production accuracy and speed. According to the UK Chemical Industries Association (2019), robotic automation has helped British companies achieve high safety standards without compromising production efficiency.

After the Toulouse accident (2001), France began investing significantly in digital integration for monitoring chemical fertilizer plants. The creation of mandatory digitalization and automation protocols resulted in greater risk predictability and reduced incidents. This case demonstrates how tragedies can be transformed into public policies for technological innovation, aligning industrial safety with increased productivity.

These international examples confirm that automation and process integration are not just academic discourse, but rather established practices in various contexts. The results point to gains in efficiency, quality, safety, and sustainability. For Brazil, these cases serve as a source of inspiration and benchmarking, indicating possible paths to modernize its chemical industry and align with global best practices.

5. Brazilian Experiences in Chemical Plant Automation

The Brazilian context presents a number of unique aspects regarding process integration and industrial automation in chemical plants. Although the country has significant industrial hubs, such as the Camaçari Petrochemical Complex in Bahia and the Petrochemical Complex in

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In São Paulo's ABC region, the adoption of advanced technologies still faces challenges related to costs, organizational culture, and infrastructure. However, recent experiences demonstrate that Brazilian companies are beginning to recognize automation as an essential strategy for increasing productivity and competing in a globalized market. According to data from the Brazilian Chemical Industry Association (ABIQUIM, 2019), investments in automation represented more than 20% of the innovation budget of large chemical companies in Brazil.

A relevant example is **Braskem,** which has invested in digitalization projects and the use of artificial intelligence in its plants. The company implemented IoT sensors to monitor critical variables, such as pressure and temperature, in real time, allowing for greater predictability and efficiency in operations. According to internal reports (Braskem, 2020), the integration of digital processes resulted in gains of up to 15% in energy efficiency and reduced unscheduled downtime at certain plants by 20%. This experience demonstrates that the application of emerging technologies is not restricted to developed countries but can be successfully adapted to the Brazilian context.

Another noteworthy case is **Petrobras,** which, in addition to its operations in the oil and gas sector, also operates in petrochemical segments. The company has invested in **digital twins.** to optimize the performance of refineries and associated chemical plants. The use of these digital twins allowed for the simulation of complex operating scenarios, anticipating failures and optimizing maintenance planning. According to studies published by Petrobras in partnership with universities (2019), the use of digital twins contributed to reducing operating costs by up to 25% and significantly increasing the reliability of critical processes.

In the fertilizer sector, Brazilian companies are also beginning to incorporate automation into their operations. Yara Brasil, for example, has adopted advanced control systems and big data tools in its production units, enabling substantial gains in production efficiency and inventory management. This type of practice reinforces the importance of automation not only for large petrochemical companies but also for strategic segments of the chemical industry focused on agribusiness, which is one of the foundations of the national economy.

Brazilian experiences also demonstrate the fundamental role of **universities and research centers** in implementing industrial automation. Projects developed in partnership with institutions such as the State University of Campinas (UNICAMP) and the Federal University of Rio de Janeiro (UFRJ) have contributed to developing automation solutions adapted to local conditions. This interaction between academia and industry reflects the **Triple Helix** model advocated by Etzkowitz and Leydesdorff (2000), which considers cooperation between government, universities, and businesses essential for innovation.

Despite the progress, challenges remain. Many small and medium-sized Brazilian chemical companies still face difficulties in adopting advanced technologies due to high costs and lack of training. This limitation widens the gap between large and smaller companies, creating a technological gap that compromises the competitiveness of the sector as a whole. Therefore, in addition to private investment, public policies

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incentives and professional training programs become fundamental to democratizing access to automation.

Thus, Brazilian experiences confirm that industrial automation is already a reality in the country, but that its full adoption depends on a joint effort between companies, government, and universities. The future of the Brazilian chemical industry necessarily depends on the ability to integrate processes, adopt emerging technologies, and create smart production plants capable of competing globally.

6. Practical Applications of Automation in Productivity

The practical applications of automation in chemical plant productivity are numerous, ranging from incremental improvements to structural transformations in the way processes are conducted. One of the most immediate applications is the **reduction of unscheduled downtime,** which represents one of the largest sources of productivity loss in industrial plants. Using IoT sensors and predictive maintenance algorithms, it becomes possible to identify equipment anomalies before failures occur, enabling planned interventions. According to data from Lee et al. (2015), this approach can reduce plant downtime by up to 30%, increasing operational availability.

Another practical application is **optimizing energy consumption,** a critical aspect in chemical plants due to the high energy costs. Advanced control systems continuously adjust variables such as temperature and pressure, ensuring that processes operate within optimal efficiency ranges. Studies by Luyben (2012) demonstrate that the use of predictive control in chemical reactors can reduce energy consumption by up to 20% without compromising product quality. This direct impact on operating costs contributes significantly to companies' competitiveness.

Automation also improves the **quality of the final product** by reducing process variability. In chemical plants, small variations can compromise the chemical composition of inputs and products, generating rework and waste. The use of digital twins and MPC allows for the prediction and correction of deviations in real time, ensuring greater uniformity. This standardization not only increases productivity but also strengthens companies' reputations in international markets, which value consistency and regulatory compliance.

Another practical impact of automation is the **reduction of occupational hazards.** By transferring critical and high-risk tasks to automated systems or industrial robots, workers' exposure to hostile environments is reduced. This aspect has a dual relevance: it protects lives and reduces compensation and workers' compensation insurance costs. Reports from the International Federation of Robotics (2019) indicate that companies that invest in robotics integrated with automation report reductions of up to 40% in workplace accidents in the chemical industry.

Automation also facilitates **integrated supply chain management,** an increasingly important factor for global competitiveness. Connected digital systems allow

Monitor inventories, logistics flows, and market demand in real time, adjusting production more precisely. This integration reduces material losses, prevents excess inventory, and enables rapid responses to demand fluctuations. Mayer-Schönberger and Cukier (2013) emphasize that big data analysis applied to the supply chain increases companies' agility and resilience.

Another practical aspect is **operational sustainability.** Automation makes it possible to monitor and reduce pollutant emissions, control water use, and optimize input recycling processes, aligning the chemical industry with international environmental responsibility standards.
This concern, in addition to mitigating regulatory risks, strengthens companies' institutional image among consumers increasingly aware of sustainable practices. Hollnagel (2011) argues that resilient systems must integrate safety and sustainability as central variables, which reinforces the importance of automation.

Therefore, practical applications of automation demonstrate that it is not limited to incremental efficiency gains, but generates profound transformations in the productivity of chemical plants. It is a process that combines technological advances, economic gains, and social benefits, consolidating automation as a central axis of the future of the chemical industry.

7. Challenges and Future Perspectives

The adoption of industrial automation and process integration in chemical plants presents challenges that go beyond technological barriers. The first is the **high cost of implementation.** Advanced control systems, IoT sensors, digital twins, and artificial intelligence-based solutions require significant investments in infrastructure and personnel training. For many companies, especially medium-sized ones, this initial cost can be prohibitive. However, return on investment (ROI) studies on automation, such as those conducted by Lee et al. (2015), demonstrate that gains in efficiency, safety, and productivity offset the investments in the medium term, reducing operating costs and increasing competitiveness.

Another significant challenge is the **professional skills gap.** The implementation of emerging technologies requires professionals capable of transitioning between different fields of knowledge, such as chemical engineering, data science, and information technology. This hybrid training is still rare in Brazil and in many developing countries, hindering the full adoption of automation. Dornelas (2018) emphasizes that technical and university education needs to be adapted to include multidisciplinary courses that prepare professionals to deal with the complexity of automated systems. Without this human capital, investments in automation risk not reaching their full potential.

Cultural resistance also poses an obstacle. In many organizations, especially in more traditional contexts, there is a fear that automation will replace human labor, generating unemployment and social instability. This perception needs to be addressed with training and professional reallocation policies, demonstrating that automation does not eliminate jobs, but transforms them, creating new, more skilled roles.

Brynjolfsson and McAfee (2017) argue that the digital revolution does not eliminate jobs, but redefines skills, requiring a restructuring of the labor market.

Another critical issue is **cybersecurity.** As chemical plants become more digitized and interconnected, their vulnerability to cyberattacks also increases.
Malicious manipulation of control systems can have disastrous consequences, including explosions, leaks, and irreversible environmental damage. Therefore, automation must be accompanied by robust investments in digital security, ensuring that data and systems are protected against intrusions. Hollnagel (2011) argues that operational resilience can only be achieved when physical and digital security work hand in hand.

In terms of prospects, the trend is toward the **global expansion of intelligent automation.** Advances in AI, IoT, and digital twin technologies are expected to accelerate, reducing costs and making their application increasingly accessible. This opens the way for chemical plants in emerging countries, such as Brazil, to adopt cutting-edge solutions without relying exclusively on technological imports. The democratization of automation is seen as one way to balance international competitiveness and reduce inequalities between companies of different sizes.

Another promising prospect is linked to **sustainability.** Intelligent automation enables greater control over emissions, waste, and energy consumption, aligning chemical plants with global standards of environmental responsibility. This integration of productivity and sustainability will be increasingly valued by investors, regulators, and consumers, who demand industrial practices compatible with contemporary environmental challenges. Mayer-Schönberger and Cukier (2013) emphasize that the strategic use of environmental data can transform the chemical industry into a benchmark for social and environmental responsibility.

Finally, **international cooperation** emerges as a strategic path. Countries that have already made progress in chemical plant automation can share experiences, protocols, and technologies with nations in the early stages. This cooperation strengthens global value chains, expands safety standards, and accelerates the innovation process. By aligning itself with these practices, Brazil has the opportunity to consolidate its position as a relevant player on the international stage, benefiting from modern integration and automation practices.

Conclusion

Process integration and industrial automation in chemical plants are strategic pillars for increasing productivity, safety, and sustainability in the 21st century. Throughout this article, we've seen that the convergence of emerging technologies—such as IoT, digital twins, artificial intelligence, and advanced control systems—has the potential to profoundly transform plant operations, making them more efficient and resilient. This transformation is not only technological, but also cultural, economic, and social, requiring new forms of management and governance.

Theoretical analysis demonstrated that automation goes beyond an operational resource: it must be understood as a strategic asset, capable of generating sustainable competitive advantage. Classic studies, such as those by Douglas (1988) and Stephanopoulos (1993), already highlighted the importance of process integration, and more recent research reinforces that, when combined with digital technologies, automation generates significant gains in productivity and quality. This conceptual basis reinforces the understanding that modern chemical plants need to be designed as intelligent systems.

The international cases analyzed, such as those of BASF, Dow Chemical, and Mitsubishi Chemical, show that automation is already a consolidated practice in developed countries, with concrete impacts on energy efficiency, cost reduction, and increased reliability. These examples demonstrate that the adoption of emerging technologies is not just a trend, but an irreversible reality in the global chemical sector. For Brazil, these cases serve as inspiration and a reference for developing national policies and strategies.

In Brazil, the experiences of companies such as Braskem, Petrobras, and Yara Brasil demonstrate that automation is also beginning to produce significant results at the local level. However, challenges related to cost, training, and infrastructure still limit the dissemination of these practices. Overcoming these obstacles depends on coordination between government, companies, and universities, in a cooperation model that resembles the Triple Helix proposed by Etzkowitz and Leydesdorff (2000). This coordination is essential to democratize access to automation and ensure that small and medium-sized producers can also benefit.

The conclusion also highlights the importance of training multidisciplinary professionals. Process integration requires chemical engineers capable of communicating with data scientists, automation specialists, and financial managers. This hybrid training is still in its infancy, but it will be crucial to consolidating the digital transformation of the chemical industry. Continuous training programs and curricular reforms in higher education are fundamental measures to prepare the new generation of professionals for the challenges of Industry 4.0.

Another key point is resilience. Automation not only increases efficiency but also strengthens plants' ability to withstand crises, anticipate failures, and adapt to external changes. This resilience will be increasingly necessary in a scenario marked by energy crises, geopolitical instability, and environmental pressures. Hollnagel (2011) emphasizes that resilience depends on the ability to monitor, anticipate, and learn continuously, aspects directly related to automation technologies.

Cybersecurity also presents itself as a challenge and a priority. The digitalization of plants increases vulnerabilities to external attacks, requiring rigorous data and system protection protocols. Confidence in automation will only be fully realized if accompanied by investments in cybersecurity that ensure the integrity and continuity of operations. This aspect should be seen as an integral part of companies' digital governance.

From an economic perspective, automation represents a strategic investment with high potential returns. Although the initial costs are high, the long-term gains in productivity, energy efficiency, and risk reduction outweigh the investment. Furthermore, Automated companies find it easier to negotiate financing and attract investors, as they convey greater predictability and reliability.

The future outlook is clear: intelligent, highly digitized chemical plants, integrated into global supply chains, and aligned with sustainability standards. Those that fail to keep up with this trend risk losing market relevance. Those that strategically adopt automation will be better positioned to respond to crises, meet environmental requirements, and compete globally.

Therefore, it can be concluded that process integration and industrial automation are not just alternatives, but strategic necessities for the contemporary chemical industry. Brazil has the opportunity to accelerate its modernization, learning from international experiences and adapting them to its context. If well-managed, this process will transform the national industry into a model of productivity, sustainability, and innovation in the 21st century.

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