Production Automation in Brazilian Pharmaceutical Industry: A Foresight Study Based on Scenario Analysis, Technology Roadmap, and System Dynamics

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This study proposes a technological foresight for automating a pharmaceutical industry production line in Brazil. To achieve this, a future scenario analysis and a technology roadmap were developed based on industrial needs identified through a literature review conducted over the past decade, along with a system dynamics mapping. The results discuss the potential impacts of automation and offer insights to guide decision-makers. This investigation could benefit pharmaceutical industries in developing countries by enabling more agile manufacturing processes and a diversified product supply to treat diseases and respond to public health emergencies.
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Technological disruptions in the Digital Age have presented significant challenges to organizational work processes, particularly manufacturing. The concept of Industry 4.0 has gained global relevance, driven by three primary factors: digitalization, integration of the horizontal and vertical value chain, and digitization of product and service supply chains through innovative business models and customer engagement [1].

A 2024 report by the Dubai Future Foundation identified "living with autonomous robots and automation" as one of the key megatrends. Initially dominant in the automotive sector, robots and process automation are increasingly penetrating other manufacturing environments, fostering efficiency and innovation while raising ethical and societal concerns [2]. Globally, task automation reached 34% in 2024 and is projected to rise to 42% by 2027 [2]. In parallel, the World Economic Forum's 2023 report on the future of work indicated that artificial intelligence is expected to increase by 75% by 2027 [3]. Although the growth rate of industrial robotics has slowed due to post-pandemic economic challenges, long-term projections suggest that service robots—especially in manufacturing, healthcare, and logistics—will expand by approximately 21.5%, particularly in the Middle East [2].

Brazil and other developing nations must invest in technological foresight to automate production lines and achieve similar advancements. Technological foresight is a strategic process for anticipating future scientific and technological developments that may influence industry, the economy, and society. It focuses on altering technological trajectories and strengthening institutional competitiveness and survival [4–6].

From an industrial standpoint, foresight helps identify trends in technology, demographics, regulations, and consumer lifestyles [7], all of which are deeply connected to innovation, research and development (R&D) management, and entrepreneurial opportunities. Foresight is particularly valuable when rapid response is needed for crises or public health emergencies, aligning with the concept of "future preparedness" [8].

Methodologically, foresight involves mapping the innovation process and examining how multiple factors and stakeholders interact to

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anticipate the outcomes and risks of technological change [4,9]. There are two primary foresight approaches: patent analysis and scenario-based methodologies. Both approaches face constraints related to time and resources [10]. While patent analysis can help industries build proprietary production platforms using emerging technologies, it often entails high costs. Sole reliance on imports of pharmaceutical products is also not viable. A more feasible strategy for countries like Brazil is to conduct technological foresight analyses that evaluate existing technologies' future configurations, identify uncertainties, and mitigate risks. This approach supports the prioritization of R&D initiatives [11]. Adequate foresight requires integrating both quantitative and qualitative methods. This study selected scenario analysis, technology roadmapping, and system dynamics to provide comprehensive conceptual, strategic, and operational insights [12].

This work is significant because it applies a combined foresight methodology to identify safe, innovative, and sustainable opportunities for technological advancement in pharmaceutical manufacturing. Therefore, this study aims to propose a technological foresight for automating a pharmaceutical industry production line in Brazil.

Materials and Methods

A literature search was conducted in the Web of Science, Scopus, and ScienceDirect databases using the query: "technology roadmap" AND "scenario" AND "industry". The goal was to identify industrial foresight applications employing a combination of these methods over the past decade (2014–2024). The search returned 388 results. Eight studies were selected after applying filters related to method relevance, smart manufacturing, and eligible publication types (articles, reviews, and conference papers). These represented generalized insights applicable to various industrial sectors, as no pharmaceutical-specific studies were found for the selected period.

Scenario Analysis

The literature review revealed key themes for identifying uncertainties in future industrial manufacturing. Six variables were selected, each representing one dimension of the STEEP framework (Social, Technological, Environmental, Economic, and Political). These variables included:

- Availability of digitally competent professionals;
- Adoption of science-based technologies (e.g., big data, cloud computing, AI);
- Sustainable practices in manufacturing;
- Agile logistics and supply chain operations;
- Openness to international markets;
- Laws and regulations for good manufacturing practices.

These served as the basis for constructing a morphological matrix, combining variable components to produce four distinct scenarios, with one column summarizing the most probable scenario configuration.

Technology Roadmap

The technology roadmap presented a sequential visualization of alternatives for automating a pharmaceutical production line. The roadmap detailed the responsibilities of actors and their interactions with the intended technologies, organized by short-term, medium-term, and long-term implementation goals [13,14].

System Dynamics

System dynamics modeling provides a simulation-based understanding of a context's structural and functional performance. It supports technology foresight by addressing disruptions and complex scenarios, informing policy and strategic decisions [15]. This method helps understand individual variable behavior and their interrelations, guiding decision-making and encouraging beneficial behavioral shifts [16,17].

A structural map of these variables and their interconnections was developed using Vensim® PLE software (Windows version 8.1.0 Double Precision x64, 2019).

Results and Discussion

A multidisciplinary team was assembled to develop the scenarios. The analysis showed that full automation of a pharmaceutical production line requires a multifactorial approach. Scenario 1, characterized by regressive conditions, appeared unlikely given the industry's current state. Most probable outcomes were aligned with intermediate scenarios (Scenarios 2 and 3), particularly due to advancements in digital skills and increasing adoption of digital technologies.

While digital tools improve productivity and reduce human error and accidents, the complete substitution of human labor remains uncertain. Emerging trends suggest a redefinition of job functions rather than eliminating human roles. Automation fosters product quality standardization but has not yet resolved all environmental sustainability challenges.

Logistical decisions rely partially on human input until organizations fully trust digital systems. In Scenario 4—the most transformative scenario—legal and political structures become decisive factors. While national market expansion seems feasible, boosted by experiences during the COVID-19 pandemic, international market entry may still face obstacles due to strong foreign competition. The configuration of these scenarios is illustrated in Table 1, which uses a morphological matrix with variables combined two-by-two to derive the most probable outcomes.

After constructing the scenarios, we developed a technological roadmap (Figure 1) to guide the full implementation of automation in the production process of a pharmaceutical industry. This roadmap considers the configurations and uncertainties identified in the previous step. It organizes them across different time horizons: short term (up to 2 years), medium term (2 to 5 years), and long term (5 to 10 years) on the horizontal axis, with the stakeholders responsible for each stage represented vertically. Beyond this timeline, the technological foresight process should be reviewed and updated periodically, in response to ongoing global developments.

To enable the implementation of automation technologies in the pharmaceutical manufacturing process, we identified several variables that influence behavior and contribute to the effectiveness of the roadmap stages. Figure 2 presents these interactions, mapped through a system dynamics analysis using the Vensim® computational tool.

Critical factors influencing the technological infrastructure in the health sector include auxiliary variables such as equipment costs, maintenance time, digital literacy, data analysis expertise, and green manufacturing aligned with ESG (Environmental, Social, and Governance) principles. Additional factors include delivery times for the domestic market, international sales potential, and the variety of products offered for future therapies. These variables play a strategic role in supporting the Brazilian Unified Health System (SUS). Their relevance stems from the growing pressure of rising healthcare costs, an aging population, the incorporation of new technologies and products, and other factors that impact the service and industrial sectors, further aggravating the country's dependence on imported health-related goods [18].

To reduce dependence and mitigate the negative impacts of legacy technological advances, this prospecting process can support Brazilian pharmaceutical industries in making informed decisions to enhance resilience. Adopting this forward-looking mindset will contribute to national progress and improve competitiveness in industrial health production with developed countries. Furthermore, it can inform government initiatives prioritizing knowledge, education, and—most importantly—innovation, thereby strengthening the Health Economic and Industrial Complex [18,19].

Table 1. Morphological matrix with scenario analysis.

STEEP contributors		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Most probable scenario
Social	Analogic x Digital competences	Old generation people working with many papers and using hard physical strength in processes	Half/half old generation and younger people working with less paper and partially using physical strength in processes	Most of professionals are younger working with no paper, less physical effort and more digitally capable	Processes totally digitally automated with no human working on production lines	Most of professionals are younger working with no paper, less physical effort and more digitally capable
Technological	Mechanical based x Digital and wireless based	Fully human-operated equipments	Part of equipments is operated by human and other part are digitally driven - Al and big data	Fewer equipments are operated by human and most part are digitally driven - Al, big data, sensors, robots	All equipments are operated by robots or remotely	Fewer equipments are operated by human and most part are digitally driven - Al, big data, sensors, robots
Environmental	Environment polluting x ESG practices	High emissions of carbon and high production trash	Low emissions of carbon and high production trash	No emissions of carbon and few production trash	Totally green manufacturing	Low emissions of carbon and high production trash
Economic-1	Dependant x Autonomous logistics	Internal logistics dependent of human action between production phases	Internal logistics few dependent of human action between production phases	Internal logistics half/half dependent of human action and robots between production phases	Internal logistics performed by robots	Internal logistics few dependent of human action between production phases
Economic-2	Strictly National x International vending	National actuation with poor visibility and fidelity by local customers	National actuation with high visibility and fidelity by local customers	National and international actuation with poor visibility and fidelity by foreign customers only	International actuation with high visibility and fidelity by customers in whole world	National and international actuation with poor visibility and fidelity by foreign customers only
Politics/Legal	Poor x Full adoption of fabrication good practices	Almost no quality warranty and standardizing of products developed	Around of 50% quality warranty and standardizing of products developed	Over than 70% quality warranty and standardizing of products developed	Totally quality warranty and standardizing of products developed	Totally quality warranty and standardizing of products developed

Figure 1. Technological roadmap for automating the manufacturing process.

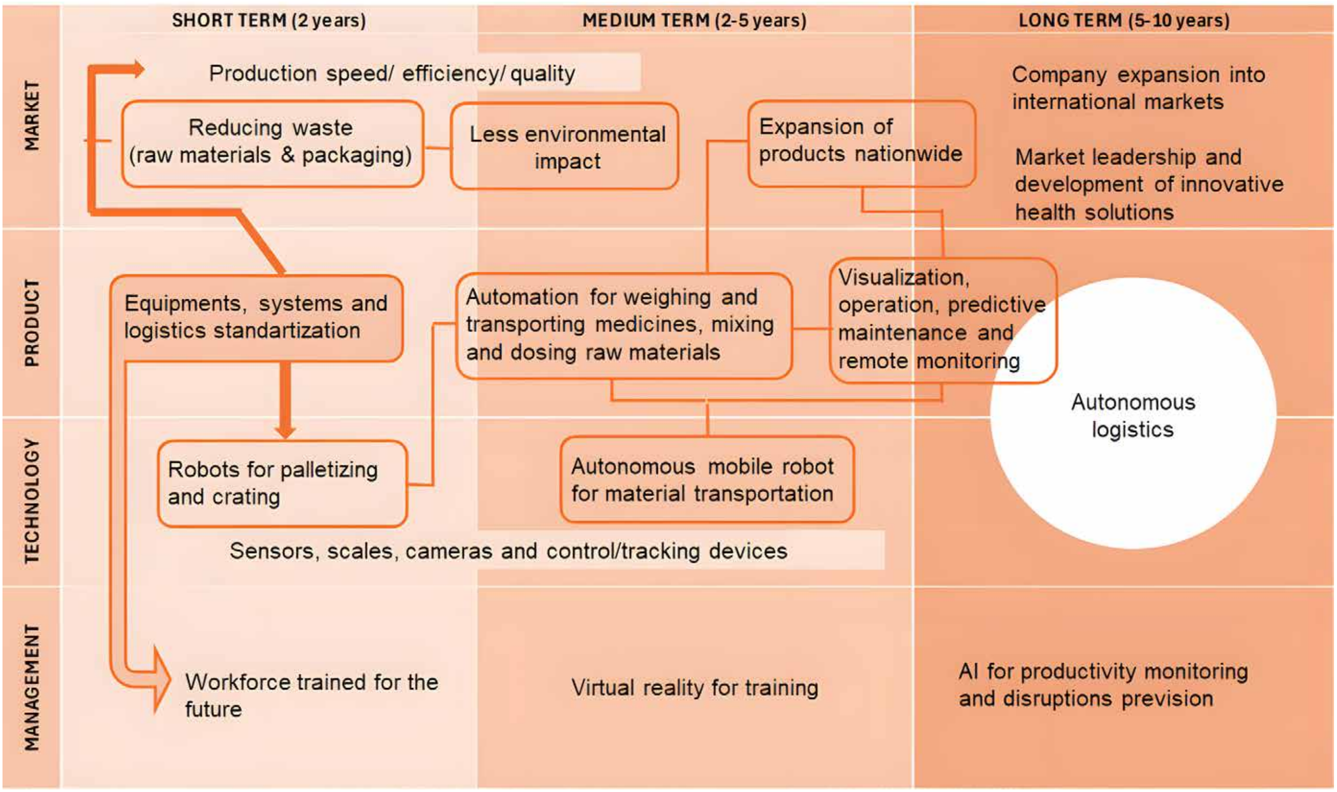
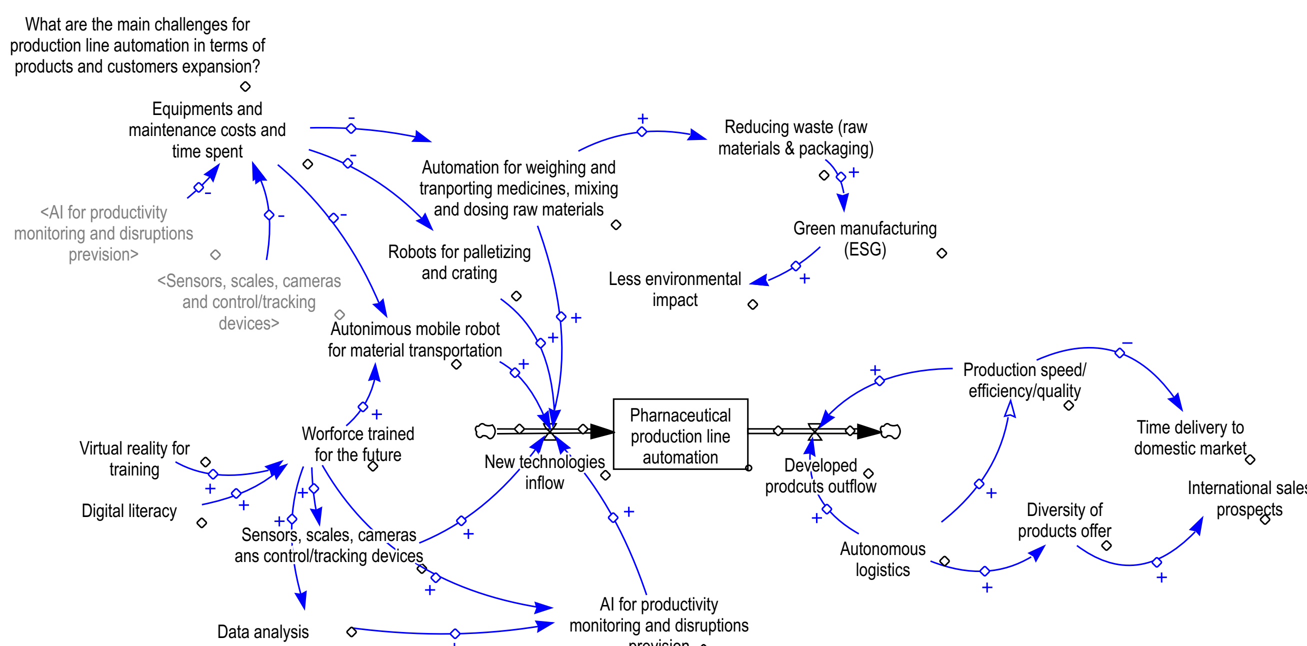


Figure 2. Dynamic analysis of the system.



To achieve this, the public and private sectors must align and articulate strategic actions, guided by insights from this technological foresight study.

These strategies should foster a high level of innovation, dynamism, and autonomy. The result will be time savings in development processes and the provision of rapid health solutions for Brazil's population and other under-resourced countries that urgently need to combat infectious diseases.

Conclusion

The foresight process represents a viable and cost-effective strategy for technological prospecting in industrial automation. It significantly reduces the financial and operational risks associated with developing new technologies.

This approach is particularly advantageous for individuals or organizations with limited technological expertise, constrained development resources, or insufficient time to engage in a complete technological development cycle, from conception through implementation.

Foresight processes prove especially valuable in contexts like the pharmaceutical industry, where multiple equipment modules must be integrated to form complex platforms or production lines. Despite requiring only a limited number of experts in future studies and situational analysis, these investigations can be highly comprehensive and effective when they incorporate complementary methods. Such a systematic approach allows for mid-course corrections and well-informed decision-making.

Moreover, a thorough and structured foresight evaluation reduces foreign dependency on healthcare technologies, streamlines production and distribution processes, and enhances national technological sovereignty. This is particularly critical for investments in bioproducts targeting diseases of primary future concern, including metabolic, chronic, and infectious diseases. It also becomes essential in scenarios demanding rapid response, such as health crises, natural disasters, or public health emergencies.

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