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DESIGN OF A NEW INDUSTRY 4.0 PRODUCTION LINE, WITH EMPHASIS ON HUMAN LABOR AND ROBOTIC SYSTEMS, BASED ON INDICATORS OF THE DIGITAL TWIN SIMULATION METHOD

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ABSTRACT
This paper presents the modeling and analysis of a new production line in the context of Industry 4.0, integrating technologies such as digital twins, collaborative robots (COBOTs), and command and supervision systems. Two scenarios are compared: a traditional production line, operated exclusively by humans, and an automated line, with human-robot interaction. The research used the Plant Simulation software to model and simulate these scenarios, evaluating indicators such as productivity, costs, operator fatigue and safety. The results showed a significant increase in productivity, improved working conditions and greater sustainability. The social and economic impacts were also discussed, with an emphasis on the need to reskill the workforce and promote safer and more ergonomic work environments.

Keywords: Industry 4.0, Digital twins, Collaborative robotics, Productivity, Sustainability, Ergonomics.

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INTRODUCTION

Industry 4.0, also called the Fourth Industrial Revolution, represents a significant transformation in production processes, integrating digital, physical, and biological technologies. It is marked by innovations such as advanced robotics, artificial intelligence (AI), the Internet of Things (IoT), additive manufacturing, and big *data analytics*, which automate processes and create smart factories. These advances, characterized by cyber-physical systems (CPS) that monitor environments and make decentralized decisions, increase the efficiency and flexibility of industrial production (BRYNJOLFSSON; MCAFEE, 2016; SMITH; JOHNSON, 2020).

Distinct from previous industrial revolutions, Industry 4.0 creates an interconnected and autonomous production ecosystem (GROOVER, 2019). Technologies such as advanced robotics optimize production and reduce risks for workers, while AI and machine learning enable predictive maintenance and cost reduction (SOUZA; OLIVEIRA, 2023; MILLER; TAYLOR, 2019). IoT connects devices in the production chain, allowing mass customization and greater operational efficiency (BRYNJOLFSSON; MCAFEE, 2016). Big *data analytics* offers valuable *insights* for process optimization and quality improvement (SMITH; JOHNSON, 2020), while additive manufacturing reduces waste and promotes flexibility in production (BRYNJOLFSSON; MCAFEE, 2016).

Industry 4.0 also requires a skilled workforce in programming, data analysis, and system maintenance, requiring continuous requalification (MILLER; TAYLOR, 2019). While it increases productivity and reduces costs, it brings challenges such as technological unemployment for lower-skilled workers. Despite this, new jobs, which require more advanced skills, emerge, reinforcing the importance of continuing education to mitigate negative impacts resulting from the lack of qualification (BRYNJOLFSSON; MCAFEE, 2016).

The rapid adoption of these technologies is essential for the global competitiveness of companies and economies, highlighting the need for public policies for education and inclusion (MILLER; TAYLOR, 2019). Reports, such as that of the *World Economic Forum* (2020), emphasize the importance of sustainable and inclusive strategies, ensuring a just transition to Industry 4.0. In addition to the most evident benefits such as greater work flexibility and cost reduction, it is crucial to balance technological advances with actions that promote inclusion and preparation of future generations (BRYNJOLFSSON; MCAFEE, 2016).

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This article aims to present a specific case of the development of robotic technology in production processes, in automated production facilities and already with access to most of the enabling technologies of Industry 4.0. In addition, its secondary objectives are the evaluation of this new work paradigm and how it can impact human productivity and current standards on work capacities, employment and professional qualification.

THEORETICAL FRAMEWORK

Industry 4.0, or the Fourth Industrial Revolution, is characterized by the convergence of the physical and digital worlds, with emerging technologies such as advanced robotics, artificial intelligence (AI), Internet of Things (IoT), additive manufacturing, and cyber-physical systems (CPS). This total interconnectivity increases production efficiency and flexibility, creating autonomous and customized factories (KAGERMANN et al., 2013; LEE et al., 2015).

Previous industrial revolutions have marked breakthroughs such as steam mechanization, electrification, and basic automation, but Industry 4.0 transcends by integrating big data, AI, and IoT for flexible production and resource optimization (BRYNJOLFSSON; MCAFEE, 2016). Core technologies include:

- **Advanced Robotics:** Collaborative robots (cobots) work side by side with humans, adapting to real-time feedback for complex tasks (SOUZA; OLIVEIRA, 2023; MILLER; TAYLOR, 2019).
- **AI and Machine Learning:** Cyber-physical systems analyze data in real-time, enabling predictive maintenance and increased efficiency (LEE et al., 2015).
- **IoT and *Big Data*:** Sensors connect devices and optimize processes, anticipating failures and reducing losses (BRYNJOLFSSON; MCAFEE, 2016).
- **Additive Manufacturing:** 3D printing creates complex parts on demand, with flexibility and less waste (Brynjolfsson and McAfee, 2016).
- **Cyber-Physical Systems:** Integrate sensors and actuators in real time, automatically adjusting operations for greater efficiency (KAGERMANN et al., 2013).

Industry 4.0 revolutionizes manufacturing, promoting unprecedented efficiency, flexibility, and customization.

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COLLABORATIVE ROBOTICS (COBOTS) AND THE AUTOMATION OF PRODUCTION PROCESSES

Collaborative robotics, known as "cobots," is a central innovation in Industry 4.0, transforming the landscape of industrial automation. Unlike traditional robots, which operate in isolation in restricted areas, cobots are designed to interact with humans in a safe and efficient manner. This interaction combines the precision and repetition characteristic of robots with the flexibility and adaptability of human workers, optimizing production processes (SICILIANO; KHATIB, 2016).

The demand for flexible automation has motivated the introduction of cobots, which offer an affordable solution for businesses of different sizes. They play a key role in improving efficiency and safety on assembly lines, especially in small and medium-sized businesses that lack the necessary infrastructure for conventional robots (Groover, 2019). Cobots enable a more affordable form of automation, ensuring an entry point for industrial modernization.

Human-robot collaboration is made possible by advanced sensors, control algorithms, and safety monitoring systems. Cobots detect human presence and adjust their operations in real-time, eliminating the need for physical barriers. In addition, their learning capacity makes them highly flexible, allowing them to quickly reschedule for different tasks and adapt to changes in the production environment. This flexibility is particularly important for industries with high product customization and variation, such as consumer goods manufacturing (BAYLIS; SARTORI, 2018; SAFFIOTTI et al., 2015).

The integration of cobots into production lines brings several advantages. Firstly, they reduce the cycle time of operations by taking on repetitive and time-consuming tasks, while human workers can focus on more complex and creative activities (VILLANI et al., 2018). This division of responsibilities increases productivity and improves the quality of the final products. In addition, cobots improve ergonomics by automating tasks that involve repetitive movements or lifting heavy loads, reducing the risk of musculoskeletal injuries and increasing worker satisfaction (Baylis; Sartori, 2018).

In the automotive industry, cobots perform high-precision tasks such as assembling electronic components and fastening screws, improving the quality and consistency of products (Villani et al., 2018). In electronics, they are used in delicate assemblies, such as printed circuit boards, where their accuracy minimizes errors and reduces worker fatigue (Groover, 2019).

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Another significant benefit is occupational safety and health. Advances in proximity sensors and motion detection algorithms allow cobots to operate side-by-side with humans, automatically stopping activities in case of excessive proximity. These safety systems have reduced the rates of occupational accidents, especially in high-tech industries (SAFFIOTTI et al., 2015; IFR, 2020).

Combining safety, flexibility, and efficiency, cobots transform the work environment, promoting ergonomics, greater productivity, and effective integration between humans and machines. They stand out as a key element for the sustainable advancement of industrial automation in Industry 4.0 (Villani et al., 2018).

IMPACTS ON THE WORKFORCE

Industry 4.0 is revolutionizing production processes and directly impacting the human workforce, transforming the nature of work, the qualifications demanded and employability. This technological revolution, based on advanced automation, collaborative robotics, and artificial intelligence (AI), increases efficiency and reduces costs. However, it significantly changes the labor market, replacing repetitive and manual tasks with more complex and digital functions (BRYNJOLFSSON; MCAFEE, 2016).

Increased automation, driven by cyber-physical systems and AI, threatens traditional jobs, especially in industries such as manufacturing, where robots replace workers on assembly lines and weldments. At the same time, new functions related to the maintenance of automated systems and programming are emerging. However, these opportunities require high qualification, making the transition difficult for workers with less schooling (MILLER; TAYLOR, 2019; SMITH; JOHNSON, 2020).

Requalification is a priority for companies and governments. Workers need to acquire skills such as programming, big data analysis, and control of cyber-physical systems. Training in languages such as Python and C++ and in emerging technologies become essential to compete in the Industry 4.0 market. Companies that offer continuous learning environments, with training programs in collaborative robotics and AI, are more successful in adapting to change (FREY; OSBORNE, 2017; Groover, 2019).

This transition also brings social challenges. Advanced automation can accentuate inequalities by favoring skilled workers while marginalizing the less prepared. Public policies focused on technical education, partnerships between universities and companies, and incentives for the creation of innovation centers are essential to ensure an inclusive

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transition. Thus, the workforce can adapt to new technological demands and take advantage of the opportunities generated by Industry 4.0 (ACEMOGLU; RESTREPO, 2020).

Collaborative robots, for example, replace humans in repetitive and physically strenuous tasks, but create new roles in supervision and analysis. In automotive manufacturing, cobots optimize assembly and inspection processes, while AI systems take over administrative and financial functions, eliminating traditional job titles. This advanced automation requires workers to evolve from operators to digital process managers, promoting a structural change in employability (VILLANI et al., 2018; FREY; OSBORNE, 2017).

To mitigate the impacts of automation, companies must invest in continuous training, while governments need to promote inclusive policies that reduce barriers to entry for lower-skilled workers. Initiatives such as certifications, tax incentives for technological training, and cooperation with educational institutions are essential to ensure a balanced transition (FREY; OSBORNE, 2017).

Industry 4.0 not only replaces jobs, but redefines work and career paths. Workers need to develop new skills to thrive in the digital environment, and the global workforce needs ongoing support to overcome the challenges of this technological transformation, making the most of its opportunities (BRYNJOLFSSON; MCAFEE, 2016).

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PRODUCTION SIMULATION TOOLS IN INDUSTRY 4.0

Digital simulation is a core element of Industry 4.0, allowing companies to optimize production processes virtually before implementing them in the real world. With advanced tools, it is possible to model and analyze scenarios, test production configurations, and predict the impact of new technologies. These simulations, aligned with the concepts of cyber-physical systems (CPS) and IoT, enable a continuous integration between the physical and digital worlds, improving efficiency, flexibility, and personalization (LEE et al., 2015; KAGERMANN et al., 2013).

Virtual simulation in production environments allows detailed modeling of industrial processes, such as the performance of production lines and workflows. With it, it is possible to minimize errors, predict failures, and adjust variables in real time, optimizing the use of resources. The analysis of historical data also facilitates the projection of impacts of changes in production processes, ensuring safer and more competitive decisions (Negahban; Smith, 2014; CHEN et al., 2020).

Tools such as *Plant Simulation*, developed by Siemens, stand out for their versatility. This *software* models factories in 2D and 3D, analyzes production capacity and optimizes logistics flows. It allows you to identify bottlenecks, evaluate changes in *layout*, and predict the impact of new technologies. Use cases have shown significant improvements, such as a 15% reduction in production cycle time and a 20% increase in resource utilization, generating important savings (Jahangirian et al., 2010; Smith; Johnson, 2020).

The application of simulators in productivity analysis is another advantage. By creating digital models, companies can monitor metrics such as production rate and cycle time, identifying areas of inefficiency. This approach also allows you to test emerging technologies, such as collaborative robotics and AI, before major investments, reducing risk and maximizing returns. Studies indicate productivity increases of up to 12% with the application of simulators (Groover, 2019; Lee et al., 2015).

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In addition to productivity, simulation helps in strategic decision-making. For example, when planning expansions or introducing new product lines, companies can predict detailed impacts on their operations, minimizing uncertainty. This ability to model complex variables makes simulation an indispensable tool for modern industrial environments (Jahangirian et al., 2010).

The integration of simulation with Industry 4.0 technologies, such as IoT and *big data*, strengthens the creation of smart factories. Data collected by sensors is used for real-time adjustments, allowing for mass customization and optimizing features. This is vital not only for efficiency but also for sustainability, reducing waste and optimizing the use of materials and energy. Simulation, therefore, not only improves industrial performance, but also promotes more sustainable practices (KAGERMANN et al., 2013; Smith; Johnson, 2020).

In short, digital simulation in Industry 4.0 transforms the production process by connecting the physical and digital worlds, offering efficient, strategic, and sustainable solutions to the demands of modern manufacturing.

SUCCESS STORIES IN THE IMPLEMENTATION OF INDUSTRY 4.0

The implementation of Industry 4.0 technologies, such as collaborative robotics, IoT, and artificial intelligence (AI), has generated notable success stories, highlighting improvements in productivity, efficiency, and quality. Audi AG has integrated collaborative robots (cobots) into its assembly lines, optimizing accuracy, consistency in production, and reducing ergonomic risks for human workers (Wehner; Schulz, 2018). At the Amberg digital factory, Siemens applied cyber-physical systems (CPS) and IoT, achieving a quality rate of 99.998%, with reduced costs and waste (Bauer et al., 2016). Another example is a packaging factory in the United Kingdom that, with AI for predictive maintenance, reduced downtime by 15% and increased productivity by 12% (Cooper et al., 2019).

Despite the benefits, automation raises concerns about employability. Studies indicate that up to 47% of jobs in the US are at risk of automation (Frey; Osborne, 2017). However, Industry 4.0 technologies also create new functions in areas such as robot maintenance, programming, and data analysis (Brynjolfsson; McAfee, 2016). Reskilling programs, such as those implemented by Bosch, highlight the importance of preparing workers for these new technological demands (Grzybowska; Łupicka, 2017).

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Comparisons between automated and traditional production lines reveal significant productivity and efficiency gains with automation. Collaborative robots allow for greater precision and less waste, while traditional lines are more flexible and adaptable, but subject to greater variability in results and operator fatigue (Groover, 2019). Despite the challenges of investment and restructuring, automated lines also improve working conditions and promote sustainable practices, reducing energy consumption and waste generation (Cooper et al., 2019).

Adopting Industry 4.0 faces challenges, including high upfront costs, resistance to change, and a lack of workforce skills. Small and medium-sized enterprises (SMEs) often face difficulties in justifying investments due to long-term financial returns (Grzybowska; Łupicka, 2017). In addition, the integration of old systems with new technologies presents interoperability and cybersecurity problems, requiring robust infrastructures and universal standards (Negahban; Smith, 2014; Bauer et al., 2016).

Cybersecurity is a growing concern, as increased connectivity in digital factories exposes systems to cyberattacks, threatening production disruptions and theft of sensitive data. Protection strategies are essential to ensure safe and reliable operations (Bauer et al., 2016).

Despite the obstacles, success stories and studies indicate that the transition to Industry 4.0 is feasible and brings significant benefits, as long as it is accompanied by investments in infrastructure, training, and management strategies. Preparing the workforce and adopting safe and sustainable practices are fundamental steps for companies to take advantage of the opportunities of digital transformation.

METHODOLOGY

To answer the research hypothesis (What are the significant impacts of the implementation of robotic technologies in Industry 4.0 production processes on productivity and on human labor and robotics?), the methodological approach adopted makes use of digital simulation. The tool selected for this purpose is the *Plant Simulation* ***software***, which allows the modeling of production processes and the creation of various scenarios for comparative analysis.

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SCENARIO CONSTRUCTION

The research uses two main scenarios, with identical characteristics of *layout* and transport systems:

- **Line A:** Operated exclusively by humans. In this scenario, all operations are manual or require human intervention (characteristic of Industry 3.0) in which productivity, costs, and fatigue levels of operators are monitored;
- **Line B:** Operated by humans in integration with collaborative robots. This scenario represents a production line in which robots and humans work collaboratively (characteristic of Ind. 4.0), with analysis of the impacts of partial automation on the aforementioned indicators.

The construction of the scenarios in the simulator follows a logical flow, based on the critical stages of manufacturing, allowing the variables of interest to be directly compared.

DATA COLLECTION IN THE SIMULATOR

The following data is extracted from the *simulation software* to feed the Fuzzy logic-based decision matrix:

1. **Productivity:** Including production rate, cycle time, and error reduction. This data is taken directly from Plant Simulation production reports, which provide a detailed view of each line's performance;
2. **Employability:** Measured by the change in the number of employees and the rate of replacement of workers. This data is simulated through the allocation of human and robot operators, and the impact this has on the workforce;
3. **Professional Qualification:** Monitoring the need for requalification of human operators to work on an automated line. The *software* allows you to simulate different levels of training and measure how it affects the efficiency of workers.
4. **Working Conditions:** The ergonomic impact and safety in the work environment are analyzed based on manual versus automatic operations, monitoring the reduction of repetitive movements and the reduction of the physical effort of the operators.

ANALYSIS FACTORS AND INDICATORS

Key indicators analyzed in the survey include:

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- **Production Rate** (units per hour): To measure the efficiency of production lines.
- **Error Reduction**: Percentage of defects eliminated with the use of robots.
- **Production Cost**: Comparison between the operating costs of a line operated by humans and one with collaborative robots.
- **Operator Fatigue**: Level of physical fatigue recorded in Line A operators compared to those in Line B, who have the support of robots.
- **Safety and Ergonomics**: Reduction of work accidents and improvement in ergonomic conditions.

ETHICAL CONSIDERATIONS AND LIMITATIONS OF RESEARCH

The research involves an in-depth analysis of the replacement of human workers by robots, which raises important ethical questions about employability and professional qualification. These aspects are treated with care in the analysis of the data, ensuring that the research does not foster the devaluation of human work.

RESULTS AND DISCUSSION

PRODUCTIVITY

It is the desire of every industry that its processes have the most efficient characteristics, making it more competitive, characteristics such as Productivity, Repeatability and Flexibility present today in the emerging technologies of industry 4.0.

Based on the simulation of the scenarios with the Digital Twin method, the results achieved in productivity gained prominence, presenting an installed capacity of the new line above 100% as shown in **fig. 1**, allowing the line to receive new product models (with its capacity for flexibility), have the available time necessary for preventive maintenance (scheduled), avoiding also sacrificing compliance with rest times (breaks) and overtime, because the line has the load capacity to recover delays produced by non-conformities and unscheduled stops (corrective maintenance).

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FIGURE 01: Production indicator of an 8:00 a.m. shift.

With the promising production results, there was also the possibility (as shown in **fig.2**) of Re-Lay Out of the process support departments, such as the warehouse, which had the resizing of the useful space with the use of COBOT's, performing the supply of the AGV's (previously done by an employee), as well as the reduction of the perimeter area that the ? AGV? must travel to supply the line. Maintenance, adapting as a support and laboratory for training (technicians and operators) and kinematic tests of the Robots as well as their programming, and a leisure or rest area for employees for breaks (Fig. 2).

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FIGURE 02: Comparison of the use of the warehouse areas after re-lay out.

COSTS

They are thus presented in **table 1** as well as the investment costs and fixed costs foreseen for the implementation of the project, where it has several items of national production, but with quotation in foreign currency, so we recommend the use of reserves in foreign currency for full payment of suppliers in the first month (period of commissioning of the machines) so that the return on investment (R.O.I) can be recognized directly with the production results.

Investment expenses are thus defined as any resource applied to the acquisition of machinery, equipment and inputs to operate a process. Fixed expenses are all resources intended for the acquisition of inputs, parts and pieces and services from third parties, to ensure the operational maintenance of equipment in their work routines, whether in autonomous, semi-automatic or manual systems. For the first month of production with a single work shift, the calculation basis for the R.O.I. is defined in the sum of investment expenses (D.O.I) and fixed expenses (D.F) and in the second month the R.O.I. calculation basis will be considered only the fixed expenses (since the investment expenses are already fully settled).

Table **1** presents the result of production with a single work shift (eight hours) for a day with a month of 22 days and a year of 11 months, since reaching a negative R.O.I for the first month, but a promising result for the second month of 265.13%, when the calculation basis in this second month, it considered only fixed expenses. In **table 2**,

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which corresponds to two work shifts, for the first month, again the investment expenses added to the fixed expenses (with emphasis on items 12-14-15-16), changed in values due to the addition of more operating expenses and their derivatives, proportionally with a larger workforce (two shifts) the production indicators presented higher results, but with negative R.O.I for the first month, and second month reaching a production margin of 365.96%. In **table 3,** considering three work shifts, we observe that there is an R.O.I in the first month of 25.76% and the second month of 413.2%.

TABLE 01: Production and billing results for a single shift of 08:00.

N	CUSTOS - PROJETO IND 4.0 2024	LINHA - IND 4.0	CLASSE	PRODUTO:	NOTEBOOCK - DELL i7	N° TURNOS
1	Técincos - Fabricante dos Robôs. (Treinamento e Comissionamento)	R$ 45.000,00	D.INV.			1
2	COBOT'S (Aquisição) X 4 UNIDADES	R$ 1.264.830,88	D.INV.	VALOR UNITÁRIO	R$ 972,18	
3	A.G.V (Aquisição) X 4 UNIDADES	R$ 480.000,00	D.INV.	IND 3.0	STATUS	IND 4.0
4	FERRAMENTAS E DISPOSITIVOS	R$ 50.000,00	D.INV.	31	PRODUÇÃO - TURNO	71
5	INTEGRAÇÃO SUPERVISÓRIO COM MÁQUINAS EQUIPAMENTO, COBOT E A.G.V	R$ 245.000,00	D.INV.	31	PRODUÇÃO - DIA	71
6	INTEGRAÇÃO DE MÁQUINAS EQUIPAMENTO AOS COBOT's	R$ 190.000,00	D.INV.	682	PRODUÇÃO - MÊS (22 DIAS)	1562
7	INTEGRAÇÃO DE PERÍMETROS DE SEGURANÇA - COBOT's	R$ 130.000,00	D.INV.	7502	PRODUÇÃO - ANO (11 MESES)	17182
8	INTEGRAÇÃO DE A.G.V	R$ 88.000,00	D.INV.	R$ 7.293.294,36	FATURAMENTO ANUAL BRUTO	R$ 16.703.996,76
9	PISTAS PARA A.G.V	R$ 72.000,00	D.INV.			
11	TREINAMENTO DE COLABORADORES JUNTO AO FABRICANTE DE COBOT'S	R$ 170.000,00	D.INV.		FATURAMENTO MENSAL BRUTO	R$ 1.518.545,16
	DESPESAS DE INVESTIMENTO	R$ 2.734.830,88		1° MÊS	FATURAMENTO MENSAL LIQUIDO	-R$ 1.632.181,97
12	ENERGIA ELÉTRICA	R$ 36.000,00	D.F		RETORNO INVESTIMENTO MÊS	-51,80%
13	MANUTENÇÃO DA LINHA	R$ 90.000,00	D.F			
14	OPERADORES (Salários) - R$ 2.300 :	R$ 11.286,45	D.F		FATURAMENTO MENSAL BRUTO	R$ 1.518.545,16
15	MANUTENÇÃO DOS COBOT's (PARTES E PEÇAS)	R$ 160.000,00	D.F	2° MÊS	FATURAMENTO MENSAL LIQUIDO	R$ 1.102.648,91
16	CUSTO COM MÃO DE OBRA ESPECIALIZADA - Técnicos (Salários) - R$ 4.000	R$ 28.609,80	D.F		RETORNO INVESTIMENTO MÊS	265,13%
17	MANUTENÇÃO PREDIAL	R$ 30.000,00	D.F			
18	ATUALIZAÇÃO DE SOFTWARE	R$ 60.000,00	D.F			
	DESPESAS FIXAS	R$ 415.896,25			DESPESAS DE INVESTIMENTOS	D.INV.
	CUSTO GLOBAL	R$ 3.150.727,13	TOTAL		DESPESAS FIXAS	D.F

TABLE 02: Production and billing results for two shifts of 08:00.

N	CUSTOS - PROJETO IND 4.0 2024	LINHA - IND 4.0	CLASSE	PRODUTO:	NOTEBOOCK - DELL i7	N° TURNOS
1	Técincos - Fabricante dos Robôs. (Treinamento e Comissionamento)	R$ 45.000,00	D.INV.			2
2	COBOT'S (Aquisição) X 4 UNIDADES	R$ 1.264.830,88	D.INV.	VALOR UNITÁRIO	R$ 972,18	
3	A.G.V (Aquisição) X 4 UNIDADES	R$ 480.000,00	D.INV.	IND 3.0	STATUS	IND 4.0
4	FERRAMENTAS E DISPOSITIVOS	R$ 50.000,00	D.INV.	31	PRODUÇÃO - TURNO	71
5	INTEGRAÇÃO SUPERVISÓRIO COM MÁQUINAS EQUIPAMENTO, COBOT E A.G.V	R$ 245.000,00	D.INV.	62	PRODUÇÃO - DIA	142
6	INTEGRAÇÃO DE MÁQUINAS EQUIPAMENTO AOS COBOT's	R$ 190.000,00	D.INV.	1364	PRODUÇÃO - MÊS (22 DIAS)	3124
7	INTEGRAÇÃO DE PERÍMETROS DE SEGURANÇA - COBOT's	R$ 130.000,00	D.INV.	15004	PRODUÇÃO - ANO (11 MESES)	34364
8	INTEGRAÇÃO DE A.G.V	R$ 88.000,00	D.INV.	R$ 14.586.588,72	FATURAMENTO ANUAL BRUTO	R$ 33.407.993,52
9	PISTAS PARA A.G.V	R$ 72.000,00	D.INV.			
11	TREINAMENTO DE COLABORADORES JUNTO AO FABRICANTE DE COBOT'S	R$ 170.000,00	D.INV.		FATURAMENTO MENSAL BRUTO	R$ 3.037.090,32
	DESPESAS DE INVESTIMENTO	R$ 2.734.830,88		1° MÊS	FATURAMENTO MENSAL LIQUIDO	-R$ 349.533,06
12	ENERGIA ELÉTRICA	R$ 72.000,00	D.F		RETORNO INVESTIMENTO MÊS	-10,32%
13	MANUTENÇÃO DA LINHA	R$ 90.000,00	D.F			
14	OPERADORES (Salários) - R$ 2.300 :	R$ 22.572,90	D.F		FATURAMENTO MENSAL BRUTO	R$ 3.037.090,32
15	MANUTENÇÃO DOS COBOT's (PARTES E PEÇAS)	R$ 320.000,00	D.F	2° MÊS	FATURAMENTO MENSAL LIQUIDO	R$ 2.385.297,82
16	CUSTO COM MÃO DE OBRA ESPECIALIZADA - Técnicos (Salários) - R$ 4.000	R$ 57.219,60	D.F		RETORNO INVESTIMENTO MÊS	365,96%
17	MANUTENÇÃO PREDIAL	R$ 30.000,00	D.F			
18	ATUALIZAÇÃO DE SOFTWARE	R$ 60.000,00	D.F			
	DESPESAS FIXAS	R$ 651.792,50			DESPESAS DE INVESTIMENTOS	D.INV.
	CUSTO GLOBAL	R$ 3.386.623,38	TOTAL		DESPESAS FIXAS	D.F

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TABLE 03: Production and billing results for three shifts of 08:00.

N	CUSTOS - PROJETO IND 4.0 2024	LINHA - IND 4.0	CLASSE	PRODUTO:	NOTEBOOCK - DELL i7	N° TURNOS
1	Técincos - Fabricante dos Robôs. (Treinamento e Comissionamento)	R$ 45.000,00	D.INV.			3
2	COBOT'S (Aquisição) X 4 UNIDADES	R$ 1.264.830,88	D.INV.	VALOR UNITÁRIO	R$ 972,18	
3	A.G.V (Aquisição) X 4 UNIDADES	R$ 480.000,00	D.INV.	IND 3.0	STATUS	IND 4.0
4	FERRAMENTAS E DISPOSITIVOS	R$ 50.000,00	D.INV.	31	PRODUÇÃO - TURNO	71
5	INTEGRAÇÃO SUPERVISÓRIO COM MÁQUINAS EQUIPAMENTO, COBOT E A.G.V	R$ 245.000,00	D.INV.	93	PRODUÇÃO - DIA	213
6	INTEGRAÇÃO DE MÁQUINAS EQUIPAMENTO AOS COBOT's	R$ 190.000,00	D.INV.	2046	PRODUÇÃO - MÊS (22 DIAS)	4686
7	INTEGRAÇÃO DE PERÍMETROS DE SEGURANÇA - COBOT's	R$ 130.000,00	D.INV.	22506	PRODUÇÃO - ANO (11 MESES)	51546
8	INTEGRAÇÃO DE A.G.V	R$ 88.000,00	D.INV.	R$ 21.879.883,08	FATURAMENTO ANUAL BRUTO	R$ 50.111.990,28
9	PISTAS PARA A.G.V	R$ 72.000,00	D.INV.			
11	TREINAMENTO DE COLABORADORES JUNTO AO FABRICANTE DE COBOT'S	R$ 170.000,00	D.INV.	1° MÊS	FATURAMENTO MENSAL BRUTO	R$ 4.555.635,48
	DESPESAS DE INVESTIMENTO	R$ 2.734.830,88			FATURAMENTO MENSAL LIQUIDO	R$ 933.115,85
12	ENERGIA ELÉTRICA	R$ 108.000,00	D.F		RETORNO INVESTIMENTO MÊS	25,76%
13	MANUTENÇÃO DA LINHA	R$ 90.000,00	D.F			
14	OPERADORES (Salários) - R$ 2.300 :	R$ 33.859,35	D.F	2° MÊS	FATURAMENTO MENSAL BRUTO	R$ 4.555.635,48
15	MANUTENÇÃO DOS COBOT's (PARTES E PEÇAS)	R$ 480.000,00	D.F		FATURAMENTO MENSAL LIQUIDO	R$ 3.667.946,73
16	CUSTO COM MÃO DE OBRA ESPECIALIZADA - Técnicos (Salários) - R$ 4.000	R$ 85.829,40	D.F		RETORNO INVESTIMENTO MÊS	413,20%
17	MANUTENÇÃO PREDIAL	R$ 30.000,00	D.F			
18	ATUALIZAÇÃO DE SOFTWARE	R$ 60.000,00	D.F			
	DESPESAS FIXAS	R$ 887.688,75			DESPESAS DE INVESTIMENTOS	D.INV.
	CUSTO GLOBAL	R$ 3.622.519,63	TOTAL		DESPESAS FIXAS	D.F

FATIGUE

Table **4** shows the distance traveled (in meters) by operators to reach workstations over the course of a shift. The values point to a considerable physical wear and tear that, at the limit of effort, can compromise the time (pace) of the line and even the quality of the product, if the task or process depends on the operator's expertise (experience – skill).

TABLE 04: Distance of the employees' displacements in the process, for an 8-hour shift.

FADIGA DE DESLOCAMENTO ENTRE POSTOS				
	TURNO	CARGA HORÁRIA	L : OPRD 1	L : OPRD 2
LINHA IND. 3.0	1	8	290 m	235,8 m
LINHA IND. 4.0	1	8	4 m	6,7 m

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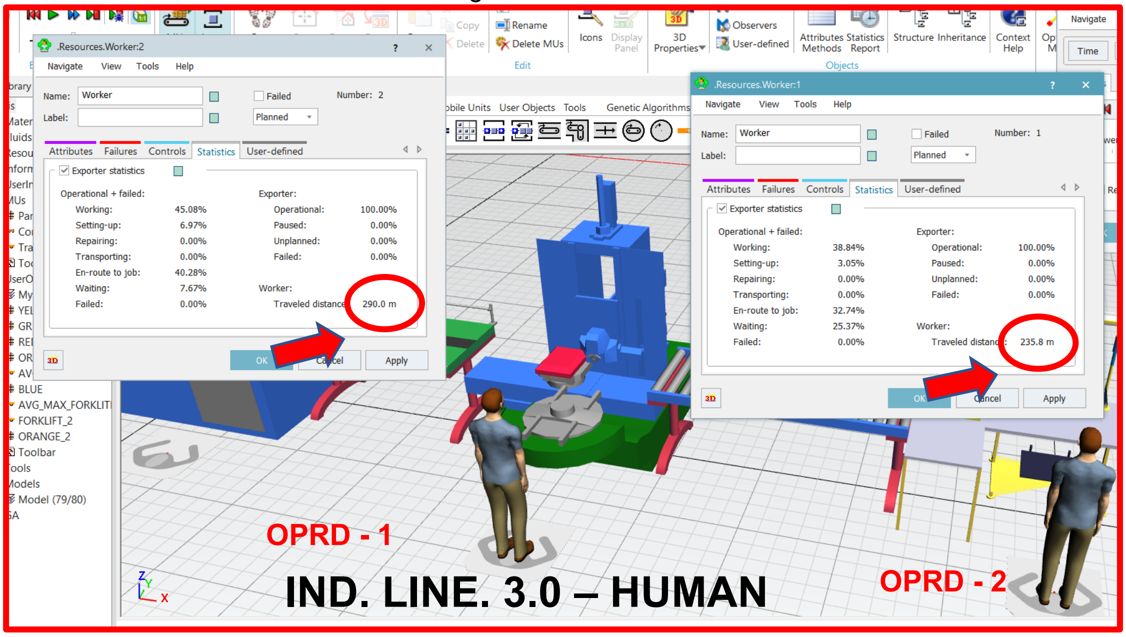
FIGURE 03: Fatigue indicators of the Ind. 3.0 line



The company's Specialized Service in Safety Engineering and Occupational Medicine (SESMT) has the physical integrity of employees as a priority of its attributions as a prevention department, so it would consider the data presented in **table 5, fig.3** and **fig. 4** in the indicator of the Ind. 4.0 line as the ideal scenario for the comfort and quality of the work environment, highlighting as such the reduction of the rates (not shown) of employee leave due to occupational diseases, elimination of overtime to recover production affected by non-compliance caused by malpractice through physical exhaustion; In this way, preventing new hires (to make up for leaves) and less payroll costs for the company.

TABLE 05: Details of the employees' displacements in the process, for an 8-hour shift

FADIGA DE DESLOCAMENTO ENTRE POSTOS					
LINHAS	**OPERADOR**	**WORKING**	**IEN - ROUTE TO JOB**	**WAITING**	**SETIING - UP**
IND. 3.0	**OPRD 1**	45,08	40,28	7,67	6,97
	OPRD 2	38,84	32,74	25,37	3,05
IND. 4.0	**OPRD 1**	40,63	0,56	51,01	7,81
	OPRD 2	45	0,92	53,03	1,05

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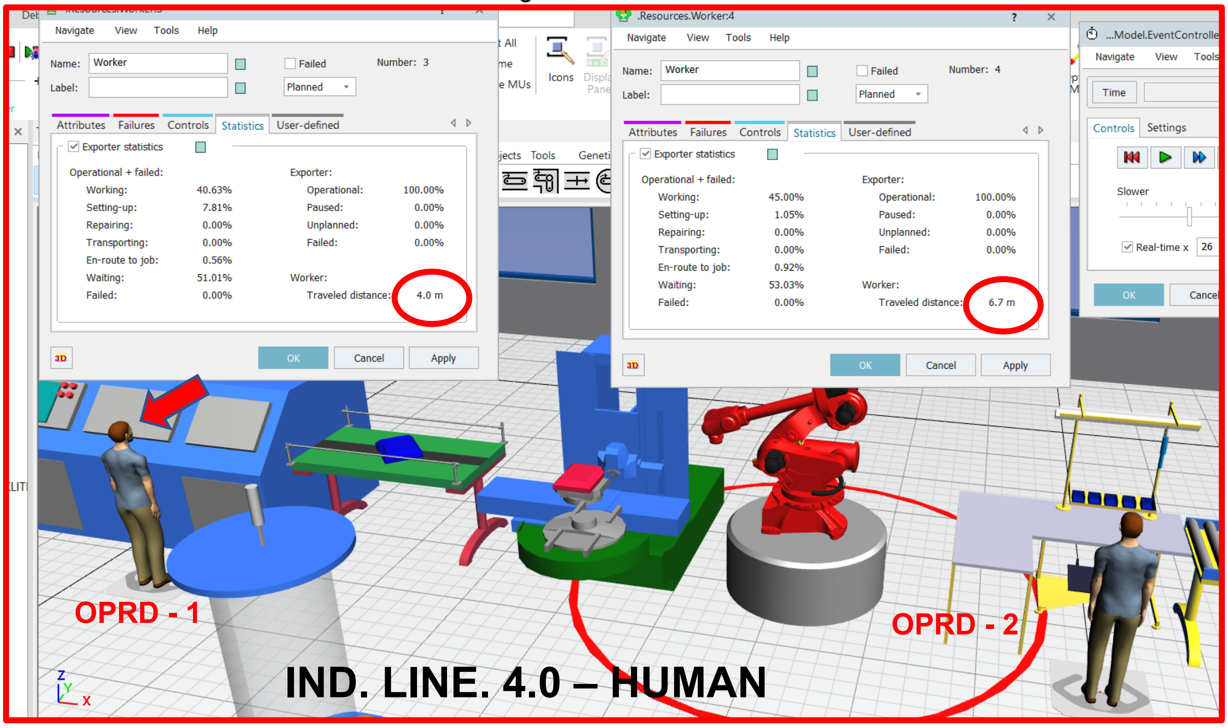
FIGURE 04: Fatigue indicators of the Ind. 4.0 line



SECURITY

The combination of smart devices, real-time connectivity and data analysis capabilities allows us to employ machines capable of learning and managing systems, such as advanced robotics in Industry 4.0, so COBOTS stand out for their AI model capable of monitoring their perimeter of action, interacting directly or indirectly with humans without the need for physical barriers through their algorithm and their learning routines.

FIGURE 05: Cobot interacting with human.

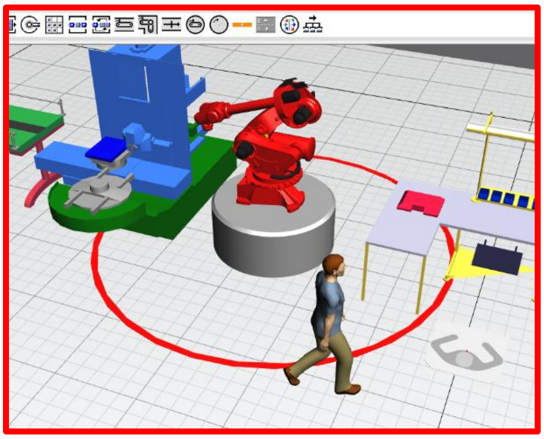


FIGURE 06: Warehouse Ind. 3.0

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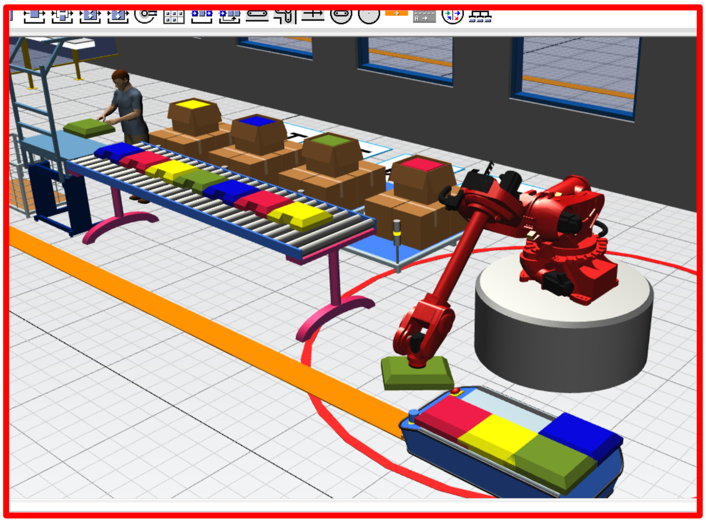
FIGURE 07: Warehouse Ind. 4.0



With an initial approach through the Industry 3.0 warehouse (**fig. 6**) we have a forklift that is supplied by the employee who also unpacks the inputs (parts and pieces) to be driven by the forklift. Fig**. 7** shows the Industry 4.0 warehouse environment where we can observe the A.G.V being supplied by a COBOT that intersperses with a conveyor belt receiving the raw material unpacked by the employee. The Robots in this fig.5 simulation project are the elements that stand out the most for their robustness and kinematic ability to perform fast and precise movements, relying on embedded systems such as touch, vision and movement sensors that are the vital organs for the machine (COBOT) to recognize the elements that compose around its work perimeter, capable of stopping its movement or process when its safety devices are triggered. The A.G.V. also have onboard sensors capable of interrupting their trajectory or deviating when an obstacle opposes the predetermined traffic perimeter.

Human fatigue caused by repetitive effort can also increase the potential for accidents through incompetence in the execution of the activity, caused by involuntary movements through the exhaustion of physical and sometimes even mental energies. For the Ind. 4.0 scenario, employees no longer impose physical condition as interaction in the process (now performed by Robots) and participate with the use of the technical and intellectual capacities developed by the training with the advent of the new process, thus moving employees away from risk zones and perimeters.

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DISCUSSIONS

The Digital Twin method through Plant Simulation was considered as the most appropriate tool for the analysis of this project, motivated by the need mainly for Increased Load Capacity, Reduction of Industrial Costs which triggered changes in physical space, Human Fatigue, Safety at Work, Energy and even in the Preservation of the Environment (environmental sector).

Evaluating the economic feasibility of the load capacity increase project is part of this study, and building the virtual scenario of the current line with the entire process database is the first step to be taken. Simulation tests with real process data were carried out and it was observed the loss of line speed with high waiting time rates (of the equipment) due to the dependence on the operator's intervention for the equipment to enter the work cycle as shown in the color pattern graph (gray) fig. 8 and table 5.

FIGURE 08: Color pattern graph.

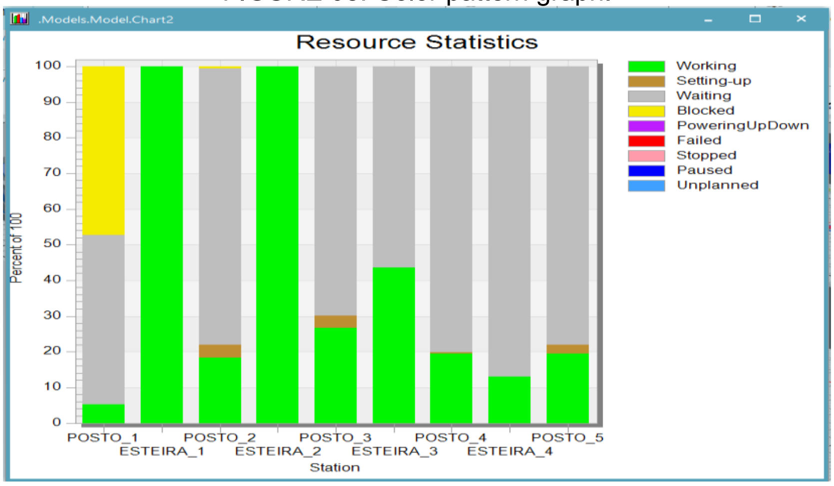
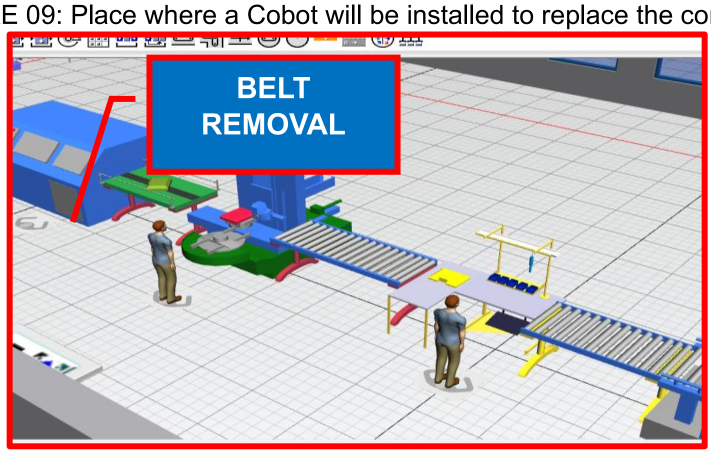


FIGURE 09: Place where a Cobot will be installed to replace the conveyor.



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Based on this scenario, we added a Collaborative Robot (COBOT) in a position of the process (fig.9) that made it unnecessary for operators to travel to perform operation command in the work cycle on the equipment. To implement COBOT, it would be necessary to invest in command and control and supervisory systems. Thus, a new virtual scenario was built using the Digital Twin method with the application of Ind. 4.0 resources, constituting a spreadsheet of costs divided into investment costs and fixed costs (**Table 1**). After adjustments in the Robot's programming, the simulation was carried out, reaching higher values compared to the current scenario.

Figures 10 and 11 show the gas stations of lines 3.0 and 4.0, respectively.

FIGURE 10: Ind. 3.0 FIGURE 11: Ind. 4.0

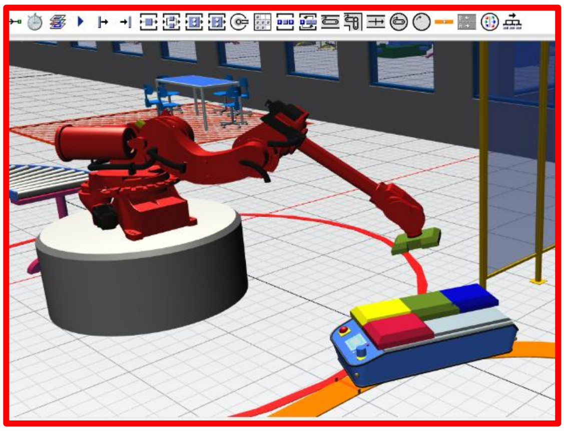

Fig. 8 also indicated a high waiting time and blockage at the line's filling station (first station of the line), represented by **Fig. 10,** where two employees perform the unloading of the forklift and the load on the conveyor belt. With the faster process, a single forklift became insufficient to supply the process and the rental of two forklifts, served the deliveries but made the station a bottleneck for the supply of the line by the two employees, in this way the operation of a Robot at this station (supply of the line) was simulated with better results, but the condition and vertical arrangement of the raw material in the forklift prevented the supply of the line from being more efficient using the Robot, in this way, we carried out a test of movement of the raw material from the warehouse to the line's filling station (already with COBOT) in an A.G.V unit, **fig. 11**, in this way, it also triggered a change in the warehouse scenario, whose scenario established in Ind. 3.0 as shown in **fig. 12** evolved to an environment of high automation as shown in **fig. 13**.

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FIGURE 12: Warehouse ind. 3.0 with emphasis on the raw material in vertical arrangement on the forklift.

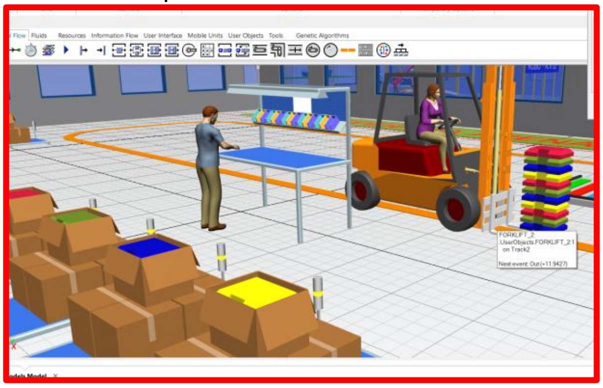
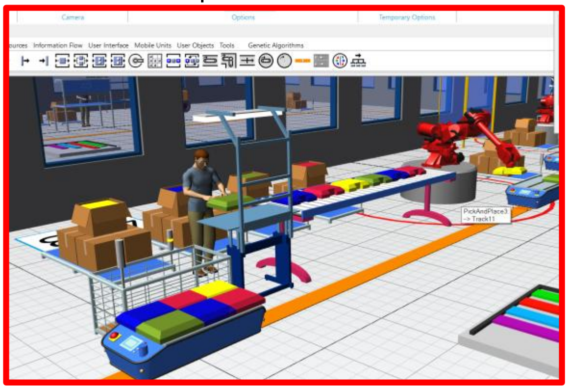


FIGURE 13: Warehouse ind. 4.0 with emphasis on the raw material being conducted by an AGV



The simulation data for the new line configuration with command, control and supervisory systems projected 71 pieces for each eight-hour shift for the Ind. 4.0 scenario compared to 31 parts in the Ind 3.0 production scenario, increasing the installed capacity of the new line to 129.03%.

For the use of these technologies, other support departments are also needed such as specialized maintenance, test lab, programmers, etc. In this case, the company must choose between the visionary condition of absorbing its surplus labor (replaced by machines), evaluating the profile, engagement and ability to adapt to the routines of new technologies by its employees. For the company, it is difficult to carry out this task of choices because some technical positions of Ind. 4.0 demand intellectual capital with an extensive workload of classrooms, an unfavorable time for the workforce that the company wants to absorb. It is worth noting that in this transitional phase of training to absorb the old workforce, new employees on a temporary basis must be hired to temporarily replace the workforce in training.

The social impact of the statistics of human jobs replaced by machines is worrying, due to the new professional demanding years of study where they will have access to

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academic disciplines focused on mathematics, physics, mechanics, electrical, electronics and programming, and this class of professional labor is still on the rise, making these professionals very competitive (disputed) by the market.

The analysis of the costs to implement the project is an important phase, in which the return on investment (R.O.I) will be evaluated and the approval for the company's management to move forward with the implementation stages. Fixed expenses correspond to 15.21% of investment expenses, for strategic reasons we recommend that all investment costs in foreign currency be paid by the first month of production that precedes the commissioning of the line, avoiding medium-term debts that may influence the financial results, in this way the R.O.I would be evaluated more accurately in the second month of production. Evaluating tables 1 – 2, the results are conclusive for a negative net monthly revenue in the first month with the line operating in up to two shifts, so to reach net monthly revenue in the first month, as shown in **table 3,** three shifts will be needed, but the R.O.I is guaranteed in the second month with the line operating with only a single shift.

COBOTS are collaborative robots with embedded technology capable of interacting with humans through their AI platform, which allows the learning of new routines in real time, providing safety to the elements of their surroundings that are part of the scenario where the work cycle will be fulfilled. If a robot interacts with a human being by providing him with an input or product, the COBOT, throughout the workload, is able to recognize the fatigue of the human being and thus reduce its operational speed. We can thus point out that safety and fatigue are interconnected in COBOTS.

Every year thousands of employees are removed from their jobs due to accidents, many in companies that operate with Ind. 3.0 technology, where physical and mental fatigue certainly stands out, triggering new hires in the industry to supply workers on leave, increasing the industry's payroll costs with temporary contracts, At the same time that these employees are away for a long period, it also produces costs for the treasury. With the advent of the application of Ind. 4.0 technologies, employees will be able to enjoy safer and more comfortable work environments, applying labor in more technical activities as shown in **fig.14**.

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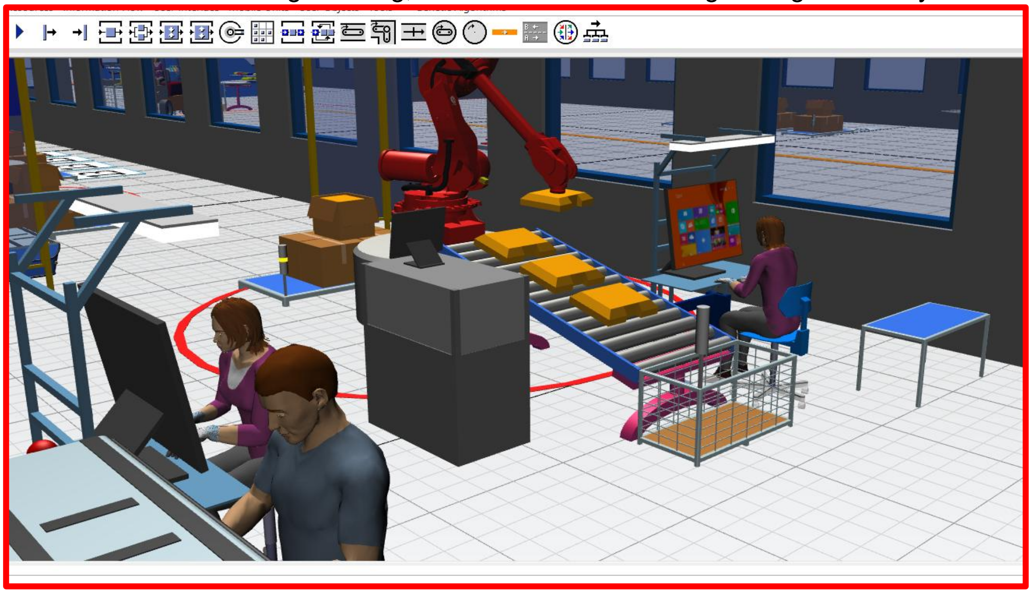
FIGURE 14: Programming, maintenance and training testing laboratory.



The environment is also indirectly benefited by Ind. 4.0. For our case study with the simulation results, the company spends less electricity producing more in the new scenario in the same cycle time as the current process. This means a lower cost in the energy bill and if the energy matrix is thermoelectric plants, less carbon will be released into the atmosphere, as well as the opportunity for the company to enter the carbon credit process, widely publicized in clean energy projects.

The increase in productivity with the application of new technologies must also ensure the quality of the product, thus avoiding statistics of non-conformities in the process and the projection of discards of non-conforming parts, either in controlled environments or in the environment. In this way, the low rate of non-compliance produced by industries that adhere to new technologies collaborates with the preservation of the environment, keeping fauna and flora safe.

FINAL CONSIDERATIONS

The study highlighted the feasibility and benefits of implementing Industry 4.0 technologies in production processes, particularly in the transition from a traditional model to an automated model with the integration of collaborative robots. The use of digital twins allowed the detailed analysis of simulated scenarios, identifying significant improvements in productivity, cost reduction, and greater efficient use of resources.

Emerging technologies, such as COBOTs, have shown clear advantages not only in increasing production capacity, but also in improving working conditions, reducing physical fatigue for operators and greater occupational safety. The application of automated systems has also demonstrated positive impacts on sustainability, with lower energy consumption and reduced waste, aligning industrial results with global environmental and economic demands.

However, the implementation of Industry 4.0 technologies requires important challenges to overcome. Among them, the need to requalify the workforce stands out, which must adapt to new technological demands. To ensure an inclusive and effective transition, it is essential that companies and governments invest in continuing education and training programs, promoting partnerships between the public and private sectors.

In addition, the successful integration of these technologies depends on investments in infrastructure and cyber-physical systems capable of connecting and optimizing production processes. The return on investment (ROI) analysis carried out showed that, although the initial costs may be high, the benefits generated, such as increased installed capacity and reduced operating costs, fully justify the adoption of the proposed solutions.

Finally, this study contributes to the advancement of knowledge about the use of Industry 4.0 technologies in production processes, reinforcing the importance of innovative solutions that promote competitiveness, sustainability, and quality of life for workers. It is recommended that future studies be carried out that explore the integration of new emerging technologies, such as artificial intelligence applied to predictive process management, to further enhance the results obtained.

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