International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XVII, No. 3 / 2025
https://doi.org/ 10.54684/ijmmt.2025.17.3.141

SIMULATION-BASED DESIGN OF ERGONOMIC RATIONALIZATION IN THE PRODUCTION PROCESS

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Abstract: Ergonomics is a crucial element in industrial engineering, contributing to the optimization of production processes while ensuring safe, sustainable, and efficient working conditions. This study focuses on simulation-supported ergonomic improvements within the production system of a selected manufacturing company. The main objective was to identify ergonomic deficiencies and propose solutions to reduce workers' physical strain. A digital model of the existing workstation was created using Tecnomatix Process Simulate software, enabling detailed analysis of worker movements and postures in a virtual environment. The RULA (Rapid Upper Limb Assessment) method was applied to assess postural load before and after implementing proposed improvements. The key intervention involved introducing spring-loaded carts to reduce frequent bending and lifting during material handling. Simulation results showed a significant decrease in the risk of musculoskeletal disorders and improvement in worker posture. The study demonstrates that integrating simulation technologies with ergonomic analysis is an effective approach to enhancing workplace conditions. This method emphasizes the value of incorporating ergonomic design early in workstation planning to improve both safety and production efficiency.
Keywords: industrial engineering, ergonomic assessment, simulation, Tecnomatix Process Simulate, ergonomic rationalization.

1. INTRODUCTION

Ergonomic rationalization in industrial environments encompasses a systematic and multidisciplinary approach to modifying the workplace with the goal of improving employee comfort, efficiency, and occupational safety. Optimization efforts typically focus on the design of workstations, including appropriate desk height, ergonomic seating, and optimal monitor placement. These physical modifications are complemented by environmental adjustments, such as proper lighting, temperature and humidity control, and the mitigation of noise and vibrations [1–3, 7].
Reducing physical workload is achieved through the development of ergonomically designed tools and the implementation of assistive technologies, including conveyor systems and material handling carts [1, 4, 8]. Employee training in correct posture and movement techniques forms an essential component of this process. Additionally, the prevention of work-related injuries and occupational diseases is facilitated through the identification and elimination of risk factors, regular ergonomic audits, and continuous evaluation of working conditions [4, 5, 9].
The improvement of employees' psychological well-being and reduction of cognitive load are supported by clear work procedures, user-friendly software interfaces, and efficient task organization [6, 10]. Organizational ergonomics addresses aspects such as appropriate scheduling of work hours and rest breaks, task allocation, and the promotion of teamwork and effective communication [10, 11].
In recent years, macroergonomic approaches have become increasingly important, integrating ergonomic principles at the organizational and system levels. This includes participatory design, management involvement, and alignment of work systems with human capabilities and limitations [11]. Moreover, psychological and cognitive ergonomics emphasize the importance of designing technology and workflows that reduce mental fatigue and increase decision-making efficiency [10].
These broader perspectives are essential when implementing ergonomics in the context of Industry 4.0, where human–machine interaction, automation, and data-driven decision-making play central roles. Although digitalization improves productivity, it can also introduce new psychosocial and cognitive risks that need to be

addressed through a proactive ergonomic strategy [8, 9].
A key element of successful ergonomic implementation is the education of both employees and management in ergonomic principles. Adherence to relevant legislative and regulatory frameworks—such as European Union directives and ISO 6385, which defines the fundamental principles of ergonomics—is essential for ensuring workplace safety and health protection [5, 12].
Ergonomic assessment serves as a fundamental tool within the broader framework of workplace optimization. Its primary objective is to identify and quantify risk factors to enable measurable improvements in workplace design and practices. The assessment process aims to align the work environment and tasks with the physical capabilities of the workforce, ensuring that job demands do not exceed workers' physical capacities or compromise their well-being. These assessment techniques allow ergonomists to systematically observe, analyze, and evaluate human movement and behavior in real working conditions. When combined with insights from anatomy and the physiological responses to exertion, these methods inform the design of effective, health-supporting work systems. A cornerstone of reliable ergonomic assessment is the use of validated, standardized, and well-documented methodologies, which ensure both consistency and reproducibility in the analysis process [7].
Among the fundamental methods used in ergonomic analysis are RULA (Rapid Upper Limb Assessment), REBA (Rapid Entire Body Assessment), the NIOSH lifting equation, OWAS (Ovako Working Posture Analysing System), and electromyography (EMG), among others. Each of these tools provides a structured framework for evaluating various aspects of biomechanical load and postural stress in occupational settings [8–10].
In parallel, advanced digital tools are increasingly used to support ergonomic analysis and simulation-based design. Siemens Tecnomatix Process Simulate, for example, allows for virtual modeling of production processes and detailed human factor evaluations. This facilitates early identification of risks, optimization of workflows, and improvement of workplace ergonomics [11–14].

2. MATERIALS AND METHODS

In the present study, we employed the RULA method as the primary tool for ergonomic assessment. RULA is specifically designed to evaluate musculoskeletal load on the upper limbs, with particular attention to the posture of the shoulders, elbows, and wrists, as well as the neck and trunk. This method is particularly suitable for occupations that involve precise arm movements or repetitive upper limb activities, such as office work or manual selection tasks [8–10].
The RULA method provides a rapid and standardized approach to identifying potentially harmful postures, allowing practitioners to assign a risk score based on the degree of deviation from neutral positions and the presence of static or repetitive movements. The resulting scores are then used to determine the urgency of corrective actions, ranging from no immediate changes to the necessity of immediate intervention and redesign.
In this study, Siemens Tecnomatix Process Simulate was utilized to support the ergonomic rationalization of the production process. This state-of-the-art software enabled the simulation and optimization of manual operations, allowing for evaluation of worker posture and workflow efficiency within a virtual environment. Using Process Simulate, we modeled key workstations and tasks, applied the RULA method to simulated postures, and iteratively tested design modifications to reduce physical strain. The digital twin created in the simulation environment provided insight into human–machine interactions and supported decisions aimed at improving ergonomic conditions [11–14].
To evaluate the ergonomic conditions of a selected assembly workstation within a manufacturing enterprise, a simulation-based analysis was conducted using Siemens Tecnomatix Process Simulate software. This advanced digital human modeling tool enabled the creation of a realistic virtual representation of the work environment, incorporating both the physical layout and the specific tasks performed by the operator. The simulation focused on repetitive manual operations typical of the workstation and was aimed at assessing the biomechanical load placed on the upper body during task execution.
The ergonomic evaluation was carried out using the Rapid Upper Limb Assessment (RULA) method, which is integrated into the simulation platform. This method allows for a systematic analysis of the postural risks associated with shoulder, arm, wrist, neck, and trunk positions. By applying the RULA tool within the simulated environment, it was possible to identify high-risk body positions and quantify their severity through standardized scoring.
The evaluation was based on a digital human model developed within the Tecnomatix Process Simulate environment. Input data included the digital representation of the workstation, the simulated posture of the

operator during task execution, and the corresponding load values associated with specific body regions. These inputs served as the foundation for quantifying musculoskeletal risks and identifying potentially harmful postures that may require ergonomic intervention.
The RULA method evaluates each relevant body part and assigns a score ranging from 1 (low risk) to 7 (high risk), reflecting the level of ergonomic strain. The method separates the assessment into two score groups: Score A (upper limbs) and Score B (neck, trunk, legs). These scores are then combined to determine the final ergonomic risk level for both the left and right sides of the body.
To validate the impact of the proposed ergonomic improvements, a post-intervention simulation and RULA analysis were conducted. This involved re-modeling the workstation layout, adjusting the operator's equipment and furniture configuration, and re-assessing ergonomic risks based on the same RULA methodology.

3. RESULTS AND SIMULATION

The results of this assessment provide valuable insights into ergonomic deficiencies and support evidence-based recommendations for workplace redesign and risk mitigation.
In the first step of the RULA analysis, the operator's field of vision at the assembly workstation was ergonomically evaluated (Fig.1).

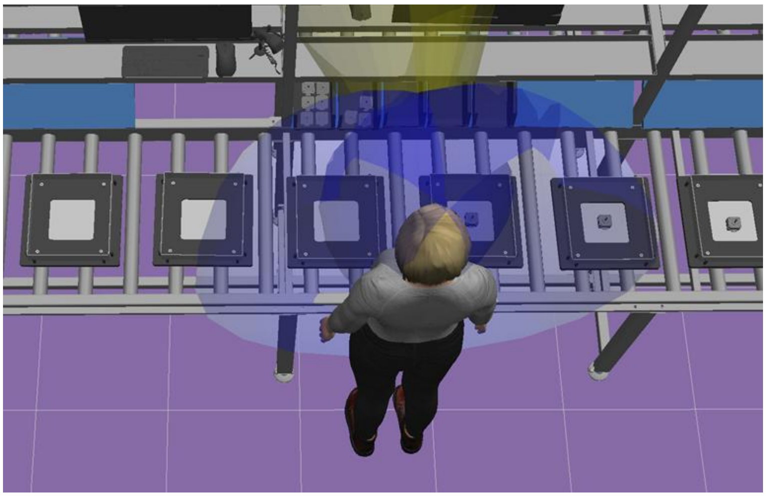

Fig. 1. Evaluation of the field of vision and reach

The results of the RULA analysis for the first segment of the work task and the corresponding working posture of the female operator are presented below. The evaluation was based on a digital human model developed within the Tecnomatix Process Simulate environment. Fig. 2 illustrates the input data used for the initial RULA assessment, which includes the digital representation of the workstation, the simulated posture of the operator during task execution, and the corresponding load values associated with specific body regions. These inputs serve as the foundation for quantifying musculoskeletal risks and identifying potentially harmful postures that may require ergonomic intervention.

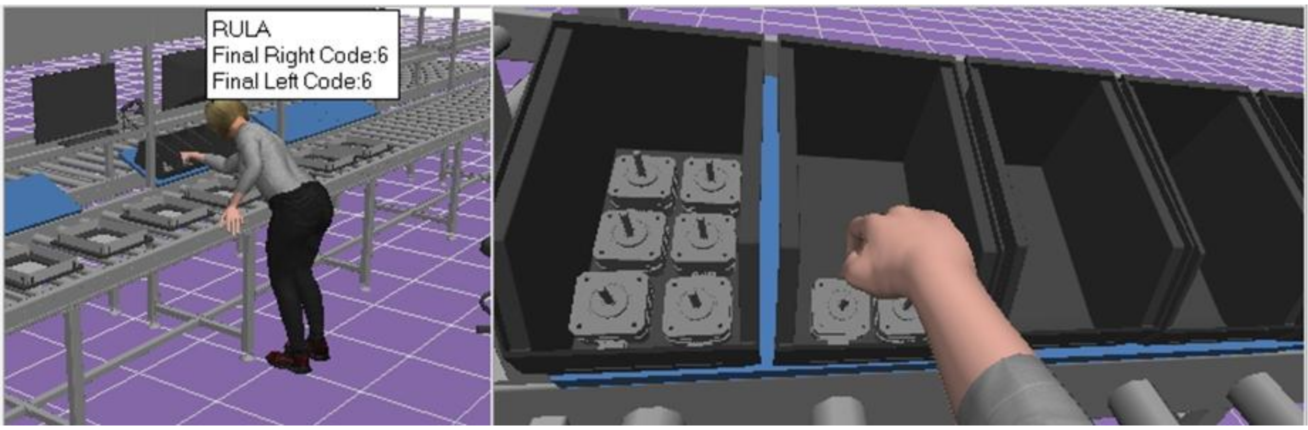

Fig. 2. Simulation of the work task

Tecnomatix evaluated each relevant body part and assigned a RULA score reflecting the level of ergonomic risk, ranging from 1 (low risk) to 7 (high risk). Upon executing the RULA analysis, numerical values were generated for each body segment, indicating the extent to which the observed posture contributes to physical strain. Fig.3 focuses specifically on the assessment of the *right upper limb*, detailing the ergonomic load associated with this body region during task execution.

TABLE A - Right									
Upper Arm	Lower Arm	Wrist							
		1 Wrist Twist		2 Wrist Twist		3 Wrist Twist		4 Wrist Twist	
		1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	6	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Fig. 3. Assessment of right arm load based on RULA analysis in Siemens Tecnomatix Process Simulate software

The combination of the *upper arm* (Upper Arm), *forearm* (Lower Arm), *wrist* (Wrist), and its *rotation* (Wrist Twist) indicates that the operator has her right hand in an inappropriate posture. A score of 6 suggests a moderate to high risk, indicating the need for adjustments to the working posture. Fig.4 focuses on the assessment of the *left upper limb*.

TABLE A - Left									
Upper Arm	Lower Arm	Wrist							
		1 Wrist Twist		2 Wrist Twist		3 Wrist Twist		4 Wrist Twist	
		1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	6	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Fig. 4. Assessment of left arm load based on RULA analysis in Siemens Tecnomatix Process Simulate software

The assessment for the left upper limb indicates a somewhat better posture compared to the right arm. A score of 5 suggests that the working posture is still risky and requires adjustment, although it is not as critical as the posture of the right arm. Fig.5 focuses on the assessment of the *neck*, *trunk*, and *legs*.

TABLE B												
	Trunk											
Neck	1 Legs		2 Legs		3 Legs		4 Legs		5 Legs		6 Legs	
	1	2	1	2	1	2	1	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Fig. 5. Assessment of neck, trunk, and leg posture based on RULA analysis in sw. Siemens Tecnomatix Process Simulate

The posture of the *neck* (Neck), *trunk* (Trunk), and *legs* (Legs) was also evaluated as moderately risky. A score of 5 indicates that the operator is likely standing or leaning in an ergonomically inappropriate position.
Based on these results, color-coded indicators were displayed on the screen, highlighting the body parts most exposed to risk. Fig.6 and Fig.7 present the final RULA scores, combining the scores for the *upper limbs* (from Table A) and the *trunk*, *neck*, *and lower limbs* (from Table B), thereby providing an overall assessment of the working posture and the associated risk level.

TABLE C Right							
Final A Score	Final B Score						
	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Fig. 6. Assessment of the right side based on RULA analysis in Siemens Tecnomatix Process Simulate software

The working posture of the right side of the body is highly risky and requires immediate intervention. This indicates that the right upper limb, in combination with the posture of the trunk and legs, is ergonomically inappropriate. It is crucial to adjust the working conditions as soon as possible, as failure to do so may lead to overexertion or injury.

TABLE C Left							
Final A Score	Final B Score						
	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Fig. 7. Assessment of the left side based on RULA analysis in Siemens Tecnomatix Process Simulate software

The left side of the body is also significantly stressed. A score of 6 indicates that the working conditions are inadequate and require changes in the short term. While it is not the highest level of risk, it is clear that the posture of the body and arms is not ergonomically suitable. Both sides of the body are subjected to excessive strain, with the right side being in a more critical condition. The results suggest the need for ergonomic adjustments to the workstation and a reassessment of the working posture to reduce health risks.
Furthermore, the current posture is unsustainable in the long term. It significantly increases the likelihood of pain and injury, particularly in the spine and shoulder areas. Both sides of the body are subjected to extreme physical strain, primarily due to the significant forward bending of the trunk (score 8) and moderately stressful positions of the upper limbs. The resulting score of 7 is at the threshold of the maximum possible risk within this methodology—working in this posture should not be performed without adjustments to the working conditions.

Based on the results of the RULA analysis, which identified the risky physical loads on various body parts of the operator, I proceeded with designing an ergonomic workstation. The objective of this phase is to rearrange the work environment to minimize physical strain and improve work efficiency. The design includes adjustments to the layout of work surfaces, the placement of tools, and components. Additionally, recommendations for the use of more suitable ergonomic furniture were incorporated, which better support posture and reduce the risk of developing health issues.

The first proposed improvement is an adjustable monitor holder, both in height and angle, as well as a separate stand for the keyboard, mouse, and barcode reader. This design allows the operator to adjust the position of the display and control devices according to individual needs, reducing static strain on the upper limbs and cervical spine. In addition, it enhances comfort and the fluidity of work when handling information.

Another key proposal to improve the workspace is an ergonomic office chair, which offers multiple adjustment options and support for various body parts. This chair is equipped with adjustable armrests, enabling the operator to relieve the upper limbs during work with the keyboard or mouse, thereby reducing muscle tension in the shoulders and forearms. The chair also features a headrest, providing support during prolonged sitting and helping to maintain correct spinal posture. The seat height, backrest tilt, and backrest height are all adjustable, allowing the chair to be tailored to different body types and the various tasks performed.

Additionally, a sliding shelf has been proposed for placing plastic transport containers with assembly parts (Fig.8). This sliding shelf enables the operator to adjust the distance and height of the work materials as needed, eliminating the need for constant bending or reaching for the containers. The goal of this design is to reduce both static and dynamic load on the spine and upper limbs during repetitive movements in assembly tasks. The sliding shelf also contributes to smoother material handling and better workspace organization. Such a solution increases the ergonomic flexibility of the workstation, allowing for quick adaptation to various types of tasks and different worker body types.

Together, these ergonomic adjustments are aimed at reducing physical strain, improving productivity, and ensuring a healthier working environment for the operator.

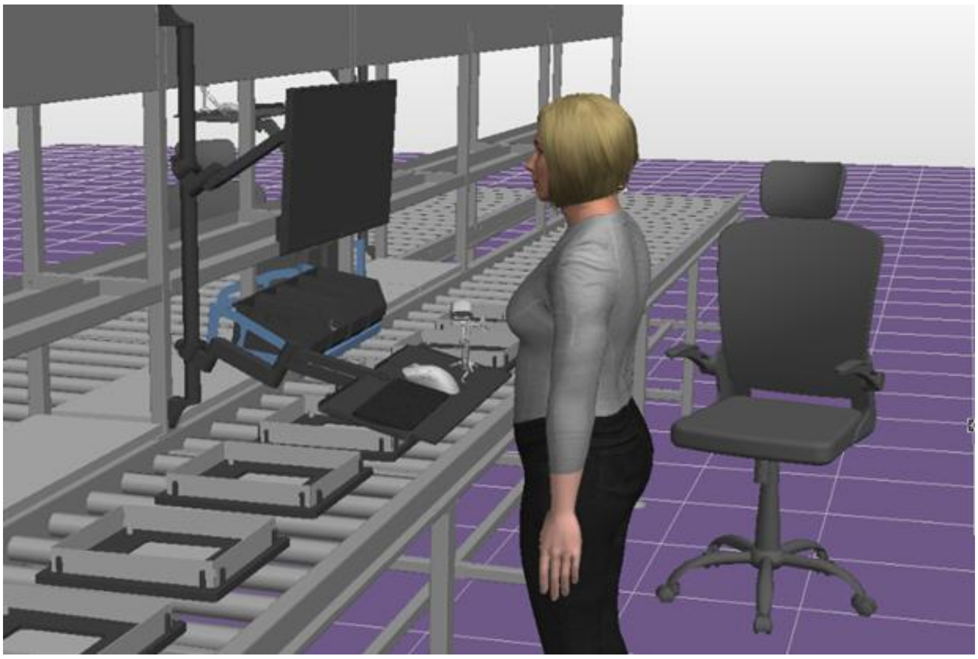

Fig. 8. Simulation of the workstation after ergonomic improvement proposals

The simulation also enabled the preparation of input data for the post-intervention RULA analysis, which aimed to confirm the improvement of ergonomic conditions following the proposed modifications (Fig. 8). Fig.9 presents the evaluation of the right arm's ergonomic load after the implementation of the proposed changes.

TABLE A - Right									
		Wrist							
		1		2		3		4	
		Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
Upper Arm	Lower Arm	1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	6	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Fig. 9. Assessment of right arm loading based on RULA analysis after the redesign in sw. Siemens Tecnomatix Process Simulate

The upper arm was assessed at level 1, indicating a neutral and relaxed position. Similarly, the lower arm was also evaluated at level 1, while the wrist, including its rotation, was rated at level 2, suggesting a position without extreme twisting. The resulting RULA score of 2 indicates that the right upper limb was in a good ergonomic posture during the evaluated task. This score corresponds to a low level of risk—no immediate corrective action is necessary, although it is advisable to monitor the posture periodically to ensure it remains within acceptable limits. Fig.10 focuses on the ergonomic load affecting the left arm after the proposed workstation adjustments.

TABLE A - Left									
		Wrist							
		1		2		3		4	
		Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
Upper Arm	Lower Arm	1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	6	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Fig. 10. Assessment of left arm loading based on RULA analysis after the redesign in sw. Siemens Tecnomatix Process Simulate

The upper arm was assessed at level 3, indicating a raised or extended position. The lower arm received a rating of 2, while the wrist and its rotation were evaluated at level 3, suggesting some degree of twisting. The resulting RULA score of 4 suggests that the left upper limb was in a less optimal posture during the observed task. This score indicates a moderate level of ergonomic risk, which may require further observation or minor adjustments to improve the posture. Fig.11 presents the evaluation of the neck, trunk, and legs after the proposed workstation redesign.

The simulation also enabled the preparation of input data for a post-intervention RULA analysis, aimed at verifying the improvement of ergonomic conditions following the proposed workstation modifications.
Fig.11 presents the post-intervention evaluation of the right side of the operator's body. The final RULA score was 2, which corresponds to a combination of Score A equal to 2 and Score B equal to 1. According to the RULA methodology, this score falls within the grey risk zone, indicating a minimal level of ergonomic risk. This result confirms a significant improvement in the working posture, with the evaluated position now considered ergonomically acceptable and not requiring any immediate corrective measures.

TABLE C Right							
Final A Score	Final B Score 1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Fig. 11. Assessment of the right side based on RULA analysis after the redesign in Siemens Tecnomatix Process Simulate software

The final RULA score of 2 for the right side, as shown in Fig.11, indicates that this part of the body is not exposed to significant ergonomic risk. The evaluated working posture is acceptable and does not require immediate corrective action.
Fig.12 presents the post-intervention RULA assessment of the operator's left side. The final score was 3, corresponding to a combination of Score A equal to 4 and Score B equal to 1. This result falls within the green risk zone, indicating a slightly elevated risk level. While the posture is generally acceptable, minor ergonomic improvements may still be considered to further reduce the load on the upper limb.

TABLE C Left							
Final A Score	Final B Score 1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Fig. 12. Assessment of the left side based on RULA analysis after the redesign in Siemens Tecnomatix Process Simulate software

4. CONCLUSIONS

Based on the findings of the ergonomic assessment conducted through the RULA (Rapid Upper Limb Assessment) methodology using the Tecnomatix Process Simulate software, several important conclusions can be drawn regarding the initial and post-intervention conditions of the analyzed workstation. The primary objective of this study was to identify ergonomic risks associated with the physical workload of a worker performing repetitive assembly tasks and subsequently propose design interventions to reduce these risks and improve overall workplace ergonomics.
The initial RULA analysis revealed multiple problematic body postures that posed a medium to high ergonomic risk. The most critical findings were associated with the right upper limb, where a final RULA score of 7 indicated an urgent need for corrective actions to prevent musculoskeletal disorders. The left side of the body, with a score of 6, also posed a significant risk, while the neck, trunk, and legs scored a 5, suggesting forward-leaning and asymmetrical postures contributing to long-term health risks.
To address these issues, simulation-based ergonomic rationalization was implemented, aligning with the core objective of this study. The interventions included adjustable monitor and peripheral mounts, an ergonomic chair with multi-point support, and a pull-out shelf for better access to materials. These design changes were digitally tested and validated through follow-up RULA analysis, providing a data-driven evaluation of the ergonomic improvements.

The post-intervention RULA scores confirmed significant enhancement in working conditions. The right upper limb achieved a score of 2, indicating minimal ergonomic risk. The left upper limb showed improvement with a score of 4, reflecting a moderate but manageable risk. Additionally, the alignment of the trunk, neck, and lower limbs improved due to better posture support and reduced need for forward bending. These results clearly demonstrate the effectiveness of simulation-driven ergonomic optimization in industrial settings.

This contribution is particularly valuable as it showcases the benefits of applying digital human modeling and ergonomic simulation tools during the design and modification of production workstations. By integrating RULA analysis with Tecnomatix Process Simulate, the study illustrates a practical and replicable approach for enhancing workplace safety and productivity through proactive design.

In the context of *Simulation-Based Design of Ergonomic Rationalization in the Production Process*, this research highlights how simulation supports evidence-based decision-making, minimizes the need for physical prototyping, and reduces implementation time and costs. It emphasizes how virtual modeling can contribute to better planning of ergonomics even before the workstation is physically realized.

Future research in this area could expand on several aspects. One possibility is the integration of dynamic ergonomic assessment tools that analyze motion sequences over time, rather than static postures. Additionally, real-time biomechanical feedback from wearable sensors could be combined with digital models to enhance the accuracy of ergonomic evaluations. Exploring the economic impact of ergonomic interventions—such as reductions in absenteeism, injuries, and productivity losses—could further validate the return on investment in ergonomic rationalization. Lastly, extending the simulation-based approach to collaborative tasks involving multiple workers or robotic systems presents another promising direction.

In summary, this study confirms that digital simulation is a powerful tool for ergonomically optimizing industrial workstations. It offers both practical improvements for employee well-being and strategic advantages for production efficiency.

Author contributions: Conceptualization, P.T., M.P., M.K. and J.K.; methodology, P.T., M.P., M.K. and J.K.; software, M.P. and M.K.; validation, P.T., M.P., M.K. and J.K.; formal analysis, M.P., P.T., M.K., and J.K.; investigation, P.T., M.P., M.K. and J.K.; resources, M.P. and P.T.; data curation, M.K., J.K., P.T. and M.P., writing—original draft preparation, M.P., M.K., J.K. and P.T.; writing—review and editing, M.K and J.K.; project administration, P.T. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of interest: There is no conflict of interest.

Acknowledgements: This article was created by the implementation of the grant project APVV-17-0258 "Digital engineering elements application in innovation and optimization of production flows", APVV-19-0418 "Intelligent solutions to enhance business innovation capability in the process of transforming them into smart businesses", VEGA 1/0508/22 „Innovative and digital technologies in manufacturing and logistics processes and system", VEGA 1/0383/25 "Optimizing the activities of manufacturing enterprises and their digitization using advanced virtual means and tools", KEGA 020TUKE-4/2023 "Systematic development of the competence profile of students of industrial and digital engineering in the process of higher education", KEGA 003TUKE-4/2024 "Innovation of the profile of industrial engineering graduates in the context of required knowledge and specific capabilities for research and implementation of intelligent systems of the future".

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Received: March 22th, 2025 / Accepted: October 14th, 2025 / Paper available online: December 20th, 2025