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Integrating simulation modelling for sustainable, human-centred Industry 5.0: ESG-based evaluation in collaborative workplaces

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ABSTRACT

This research explores the role of simulation modelling in the development of human-centred, sustainable manufacturing processes in the context of Industry 5.0. We analyse collaborative workplaces where humans and collaborative robots (CR) work together, emphasizing the environmental, social, and governance (ESG) criteria. The research work focuses on how personalized CR parameters and optimized work environments contribute to improved productivity, well-being, and sustainability. Through simulations, the paper evaluates the operational efficiency of both manual assembly and human-robot collaborative (HRC) setups, providing insight into the economic, environmental, and social impacts of Industry 5.0 manufacturing systems. The results show significant improvements in sustainability, productivity, and worker well-being achieved through adaptive CR integration and ESG-driven engineering practices.

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1. Introduction

In the rapidly evolving landscape of industrial manufacturing, the transition from Industry 4.0 to Industry 5.0 [1] marks a paradigm shift toward human-centred and sustainable production systems [2]. While Industry 4.0 focused on automation, digitization, and connectivity [3], Industry 5.0 emphasizes the integration of advanced technologies with human well-being as a main optimization goal [4]. This transformation addresses the multiple objectives of enhancing productivity and fostering a sustainable, ethical, and socially responsible global competitive manufacturing environments [5, 6].

A significant challenge in manufacturing today lies in achieving optimal synergy between humans and collaborative robots (CRs), while maintaining a balance among economic performance, worker well-being, and environmental sustainability [7, 8]. Current manufacturing systems are often either overly automated (lacking manufacturing flexibility) or heavily reliant on manual labour (with a lack of suitable labour force), leading to inefficiencies in resource utilization, high operational costs, worker fatigue (physical and physical), and inconsistent quality [9]. Furthermore, while Environmental, Social, and Governance (ESG) criteria are increasingly emphasized in industrial settings, existing systems frequently fail to integrate these metrics effectively into the design and evaluation of collaborative workplaces [10, 11]. A lot of research works are trying to answer the question: Can growing field of Human-Robot Collaboration (HRC) offers a promising solution to obtain efficient competitive manufacturing systems [12]? HRC systems combine the precision, speed, and reliability of robots with the creativity, flexibility, and problem-solving capabilities of humans [13]. Various implementations of HRC have demonstrated improvements in production efficiency, reduced worker fatigue, and enhanced products quality [14]. Simulation modelling has also emerged as a powerful tool for analysing and optimizing these systems, enabling the evaluation of production processes under different scenarios without disrupting real-world operations [15]. Among existing solutions, simulation-based evaluations of HRC systems stand out as the most effective approach. These models provide a holistic view of production processes, incorporating economic, environmental, and social factors into performance assessments. By simulating dynamic interactions between humans and robots, these tools help identify bottlenecks, optimize task allocation, and evaluate ESG impacts [16]. Despite its potential, the current simulation-based methods face significant limitations [17]. Most models focus heavily on economic performance while neglecting the social aspects of manufacturing, such as worker well-being, safety, and engagement. Additionally, few studies effectively integrate environmental and governance criteria, such as energy efficiency and ethical labour practices, into the simulation frameworks [18]. This lack of comprehensive models hinders the ability of manufacturers to design truly sustainable and human-centred systems, particularly in the context of Industry 5.0 [19, 20].

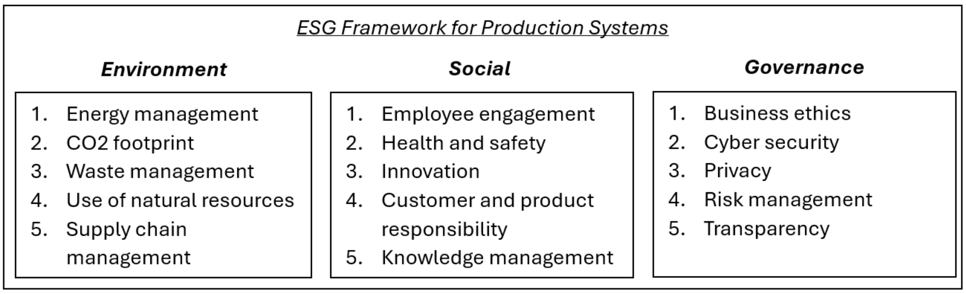
This research aims to address these limitations by developing a simulation-based approach that evaluates collaborative workplaces through the lens of ESG criteria [21]. By incorporating real-world data, the paper seeks to:

- Enhance economic performance by reducing operational costs, idle times, and energy consumption.
- Improve worker well-being by redistributing repetitive and physically demanding tasks to robots, thereby reducing fatigue and enhancing safety.
- Promote environmental sustainability by minimizing energy usage and waste generation.
- Strengthen governance practices by aligning production processes with ethical and regulatory standards.

Paper research goal is to provide a framework for designing human-centred and sustainable manufacturing systems, enabling the realization of Industry 5.0 principles in diverse industrial settings [22, 23]. This study contributes to the existing body of knowledge by demonstrating how simulation modelling can bridge the gap between productivity and sustainability, offering actionable insights for optimizing human-robot collaboration while meeting ESG goals.

2. Problem description

In the context of Industry 5.0, where the integration of human-centred and sustainable practices is crucial, the need for effective simulation modelling to evaluate manufacturing systems from an ESG (Environmental, Social, Governance) perspective has become critical. While Industry 4.0 emphasized the integration of automation and data-driven systems, Industry 5.0 highlights the necessity of aligning technological advancements with human well-being and environmental sustainability. The ESG framework, presented in Fig. 1, provides comprehensive criteria's for assessing the impact of manufacturing processes, but there remains a significant gap in evaluating collaborative workplaces especially those involving human-robot collaboration (HRC). The ESG framework shown in the Fig. 1 emphasizes the integration of sustainable, ethical, and socially responsible practices into production systems. By adopting this framework, production facilities can monitor and improve their impact on the environment, enhance worker conditions, and considering governance regulations. Simulation models, when integrated with these ESG criteria, can help optimize production systems while balancing productivity with sustainability, aligning closely with Industry 5.0 principles.



ESG Framework for Production Systems

Environment

1. Energy management
2. CO2 footprint
3. Waste management
4. Use of natural resources
5. Supply chain management

Social

1. Employee engagement
2. Health and safety
3. Innovation
4. Customer and product responsibility
5. Knowledge management

Governance

1. Business ethics
2. Cyber security
3. Privacy
4. Risk management
5. Transparency

Fig. 1 Proposed ESG framework for production systems

Existing models are often limited with the social aspects of worker well-being, which are essential for long-term operational efficiency. This gap is particularly notable in production processes supported by the concepts of the Industry 5.0, where technology must not only optimize productivity but also support sustainable and socially responsible practices. To address this issue, this research work proposes a simulation-based approach to evaluate HRC based on ESG metrics, specifically focusing on the integration of environmental sustainability, social impacts, and governance in decision-making processes. Our research emphasizes the role of human-centred design in optimizing production systems, ensuring that both economic efficiency and worker well-being are balanced through simulation.

Fig. 2 illustrates the evaluated production process in a typical dynamic job shop manufacturing environment, where machines and human workers share tasks. The figure provides a layout of the production line, showing how each machine (from M1 to M7 and manual assembly workplace WP1) interacts within the production process. The machines M1 to M7 include the following: M1 and M7 are KUKA KR 40 industrial robots. Machines M2 and M3 are Haas UMC 500 5-axis CNC centres, while machines M4 and M6 are Okuma MA 550-VB 3-axis CNC machine centres. Machine M5 is a Mazak QTS 200 model CNC machine. WP1 presents manual assembly operation, which will be replaced by HRC for the purpose of ESG simulation model evaluation. We will present how this change influence entire manufacturing system in corelation to Industry 5.0 aspects.

Table 1 presents the real-world data collected from the evaluated production process, including costs associated with machines, worker involvement, and energy consumption across multiple machines from M1 to M7 and manual assembly workplace WP1. These parameters are critical in calculating the ESG Index, as they reflect the economic, environmental, and social impacts of the manufacturing process. The table highlights key metrics which was used for calculating Total machines and WP1 costs presented by the processing and idle costs. These parameters are then incorporated into data drive simulation model to assess the production system's sustainability performance, focusing on reducing energy and scrap rate, electrical energy consumption and optimizing worker conditions while maintaining production efficiency.

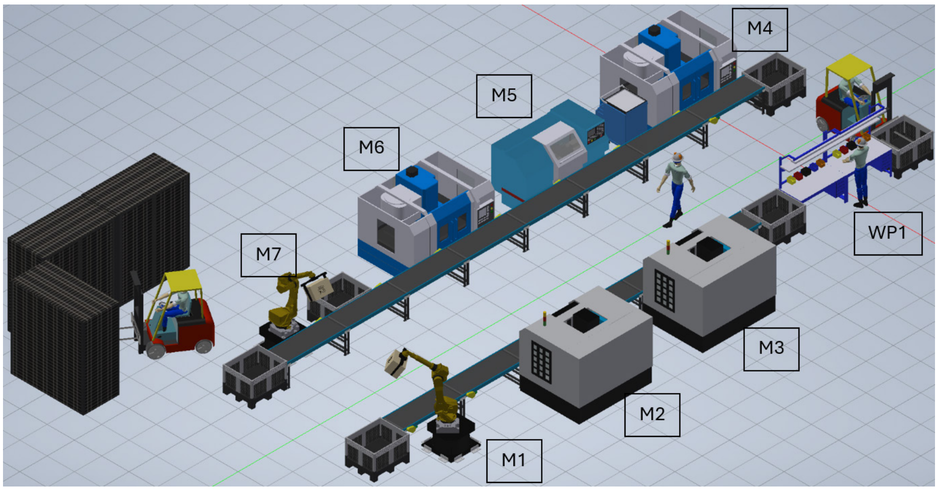


Fig. 2 Evaluated production process

Table 1 Production process real-world data

Cost calculation parameter	M1	M2	M3	WP1 (MA/HRC)		M4	M5	M6	M7
Purchase value of the machine (1000 of €)	40	140	140	31.25	6.25	150	50	150	40
Machine power (kW)	3.75	20	20	0.05	0.15	20	7.5	20	3.75
Workplace area (m^2)	8.5	8.8	8.8	1.7	1.7	17.5	4.2	17.5	8.5
Depreciation period (year)	5	5	5	5	5	5	5	5	5
Useful capacity (h/year)	4649	4649	4649	4649	4649	4649	4649	4649	4649
Machine write-off value (€/h)	1.72	6.02	6.02	1.34	0.27	6.45	2.15	6.45	1.72
Interests (€/h)	0.26	0.90	0.90	0.20	0.04	0.97	0.32	0.97	0.26
Maintenance costs (€/h)	0.26	0.90	0.90	0.20	0.04	0.97	0.32	0.97	0.26
Workplace area costs (€/h)	1.828	1.893	1.893	0.366	0.366	3.764	0.903	3.764	1.828
Energy consumption costs (€/h)	0.3	1.6	1.6	0.004	0.004	1.6	0.6	1.6	0.3
Workplace tool costs (€/h)	0.17	0.60	0.60	0.13	0.03	0.65	0.22	0.65	0.17
Total machine costs (€/h)	4.54	11.92	11.92	2.25	0.75	14.40	4.51	14.40	4.54
Worker costs (€/h)	6	6	6	15	15	6	6	6	6
Additional costs (€/h)	0.07	0.18	0.18	0.03	0.01	0.22	0.07	0.22	0.07
Workplace total processing costs (€/h)	10.61	18.10	18.10	17.29	15.76	20.61	10.58	20.61	10.61
Workplace total idle costs (€/h)	5.30	12.13	12.13	17.29	15.76	13.81	5.29	13.81	3.5

To evaluate the sustainability of collaborative workplaces, the simulation model integrates the following ESG-related metrics:

- Energy consumption was modelled based on machine power (as shown in Table 1). Energy-efficient processes are simulated to compare their impacts on overall production costs.
- Worker costs and utilization rates from Table 1 are used to simulate worker efficiency.
- Governance aspects such as worker effective capacity planning with regulations and ethical labour practices are integrated as constraints in the simulation, ensuring that the production process reflects high standards of corporate responsibility.

By combining these factors, the simulation model provides a comprehensive ESG-based evaluation of the production system, identifying areas for improvement in production efficiency, sustainability and worker well-being, from a human-centred perspective.

3. Methodology

This research work uses simulation modelling to evaluate the sustainable performance of collaborative and manual workstations, incorporating real-world data and simulation environment Simio to analyse both the economic, environmental, and social (ESG) metrics. The simulation scenarios are developed to assess how collaborative workplace and manual assembly workstation perform in terms of production efficiency, worker well-being, and environmental impact in an Industry 5.0 context. The production system, consists of machines from M1 to M7, operates under two distinct setups:

- Manual assembly WP1, human worker performs assembly tasks, with no collaborative robot assistance.
- HRC WP1, human worker is assisted by collaborative robot in assembly tasks, reducing human workload.

Each machine and WP1 operate based on actual production data from the factory floor. The following assumptions and parameters were included in the simulation model:

- Effective production system capacity is 4649 hours/year, where 252 working days/year is considered, with 3 shifts/day, 7.5 effective working hours/shift with the 82 % production process efficiency are assumed.
- The hourly salary rate for workers operating machines M1 to M7 is 18 EUR/h, with three workers required to supervising all seven machines. For manual assembly workstation WP1, one additional worker is needed with salary of 15 EUR/h.

- The electrical energy cost is 0.16 EUR/kWh, with machine-specific power consumption included in the analysis. In addition, electrical energy consumption for each machine is based on its power rating, where used value is presented by 50 % of individual machine maximum power consumption.
- Operational and idle costs are included as calculated in Table 1, where maintenance costs are 3 %, tool costs are 2 % and additional machine costs are 1.5 % of the machine purchase value.
- The conveyor belt in the system operates at a speed of 0.75 m/s, while the forklift moves at 2 m/s, with loading and unloading times of 10 s each.
- Simulation time was 92 h with the warm-up period of 8 h.

Table 2 outlines the parameters used for modelling the manual assembly workstation WP1 and the associated machines. Processing time of the machines ranges from 15 s (M1) to 85 s (WP1) at the manual assembly workplace. Processing time of the WP1 is modelled by random normal distribution, where 85 s present mean value and 12 s its standard deviation (85; 12). Electrical energy power is given such as M2, M3, M4, and M6 consume 20 kW, while others like M1 and M7 consume 3.75 kW. WP1, a manual workstation, uses only 0.05 kW. Calculated workplace total costs for each machine's ranges from 10.61 EUR/h (M1, M7) to 20.61 EUR/h (M4, M6). For the manual assembly workplace scrap rate of 8 % is modelled. Data in Table 2 serves as a baseline for modelling manual assembly WP1 production process.

Table 2 Manual assembly WP1 modelling parameters

	Machine/workplace							
Simulation model parameter	M1	M2	M3	WP1	M4	M5	M6	M7
Processing time (s)	15	35	40	85; 12	40	60	35	25
Machine power (kW)	3.75	20	20	0.05	20	7.5	20	3.75
Workplace total processing costs (€/h)	10.61	18.10	18.10	15.76	20.61	10.58	20.61	10.61
Workplace total idle costs (€/h)	5.30	12.13	12.13	15.76	20.61	10.58	20.61	10.61
Scrap rate (%)	-	-	-	8	-	-	-	-

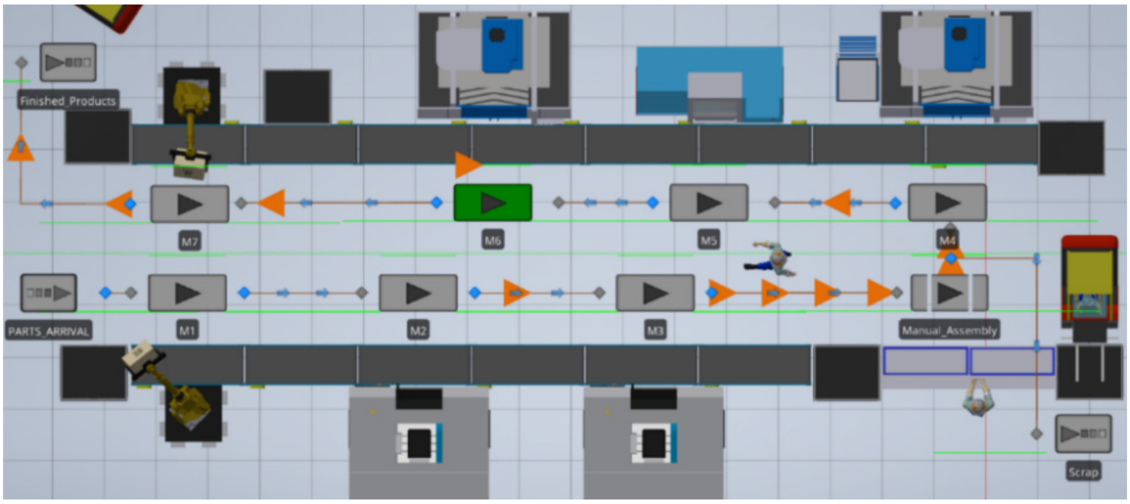


Fig. 3 Manual assembly production system model

Fig. 3 presents the configuration of the production system with the manual assembly workplace WP1, showing how machines (M1-M7) and the manual assembly workstation (WP1) are laid out in the production process. It visualizes the interactions between machines and workers, providing a clear representation of how simulation model inside Simio software is modelled in correlation to the real-world data.

Table 3 presents simulation modelling parameters for WP1 where manual assembly operation is replaced with the HRC workplace. In relation to the manual assembly operation, processing times for the machines from M1 to M7 remain the same, but for WP1 with HRC, the processing time is significantly reduced to 55 seconds with a standard deviation of 6 seconds, compared to 85 seconds in the manual assembly operation. From an environmental perspective, the scrap rate of the HRC WP1 shows an improvement in production quality, with a reduced scrap rate of 4.5 %, compared to 8 % modelled at the manual assembly WP1.

Fig. 4 visualizes the layout of the production system with the HRC WP1, where collaborative robot performs assembly tasks with human worker. The model presents how human-robot collaboration can reduce task processing times and improve overall system efficiency by optimizing the task allocation for CR and workers.

The simulation model compares two scenarios (manual assembly operation vs. collaborative workstations), using the ESG framework described in Fig 1. Key performance indicators of energy consumption, scrap rate, worker utilization, processing and idle costs rates are evaluated to identify areas for improvement the economic, environmental and social sustainability. By incorporating ESG metrics and scenario-based analysis, the study demonstrates the potential for HRC to optimize production systems while improving worker well-being.

Table 3 HRC assembly WP1 modelling parameters

	Machine/workplace							
Simulation model parameter	M1	M2	M3	WP1	M4	M5	M6	M7
Processing time (s)	15	35	40	42; 6	40	60	35	25
Machine power (kW)	3.75	20	20	0.05	20	7.5	20	3.75
Workplace total processing costs (€/h)	10.61	18.10	18.10	17.29	20.61	10.58	20.61	10.61
Workplace total idle costs (€/h)	5.30	12.13	12.13	17.29	13.81	5.29	13.81	3.5
Scrap rate (%)	-	-	-	4.5	-	-	-	-

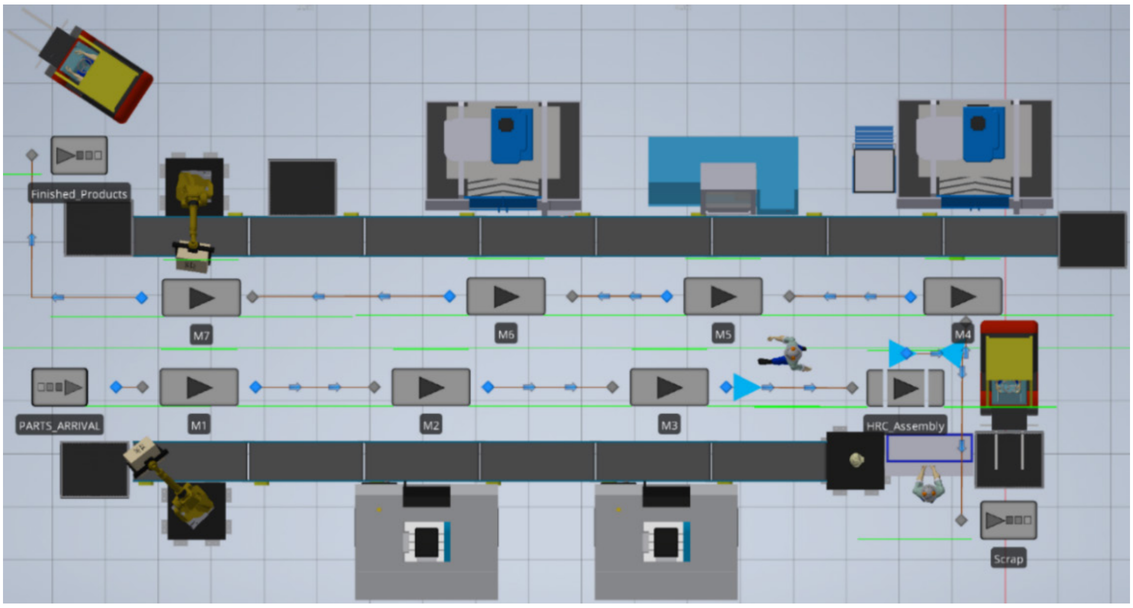


Fig. 4 HRC assembly production system model

4. Results

The simulation model was run to compare the performance of manual assembly operations with HRC at the WP1 in terms of utilization, power consumption, processing and idle costs, output quantity and scrap rate. The results highlight the differences in production efficiency, energy use, and operational costs between the two setups, emphasizing the benefits of HRC in achieving Industry 5.0 objectives. In Table 4, the utilization of the manual workstation WP1 reached a high value of 98.9 %, reflecting the bottleneck of the production process. However, several machines such as M1 (35.7 %), M4 (43.7 %), and M7 (27.3 %), exhibited significantly lower utilization, indicating unequal machine balancing. Total power consumption in the manual assembly setup was relatively high for the major machines. M2 and M3 consumed 1532.7 kW and 1751.7 kW, respectively, while WP1, being largely manual, consumed just 4.5 kW. The processing costs for the manual setup remained high, particularly for machines like M3 (€1585.3) and WP1 (€1434.0). The manual operation incurred significant idle costs for machines such as M7 (€709.6), demonstrating inefficiency in resource utilization. The manual assembly system produced 3613 finished products, with 289 scrap products, representing an 8 % scrap rate, supported by the real-world modelled parameter.

Table 4 Simulation model results of the manual assembly WP1

	Machine/workplace							
Simulation model parameter	M1	M2	M3	WP1	M4	M5	M6	M7
Utilization (%)	35.7	83.3	95.2	98.9	43.7	65.5	38.2	27.3
Machine power consumption (kW)	123.2	1532.7	1751.7	4.5	804.1	452.0	702.9	94.2
Processing costs (EUR)	348.5	1387.1	1585.3	1434.0	828.6	637.6	724.3	266.5
Idle costs (EUR)	313.5	186.4	53.6	15.9	1067.5	335.8	1171.8	709.6
Number of finished products (pcs)	3613							
Scrap products (pcs)	289							

In contrast, the HRC workstation WP1, presented in Table 5, utilization slightly decreased to 95.9 %, but this reduction was compensated by a significant increase in the utilization of other machines. For example, M4 utilization improved to 90.9 %, and M7 to 41.6 %, showing that HRC distributes the workload more evenly across the manufacturing system. In the HRC scenario, the power consumption for WP1 increased to 13.2 kW due to the CR integration. However, more efficient operation across the system led to better overall energy usage, with M4 consuming 1672.6 kW, much higher than the manual setup but justified by improved product workflow. Processing costs increased for WP1 (€1525.5) due to the CR integration investments costs but resulted in an overall improvement in resource use. The idle costs for machines like M7 decreased to €570.1, indicating better synchronization between human and CR activities. The HRC system produced 5515 finished products, a significant improvement while scrap products increased to 344 products, reducing the scrap rate to 4.5 %. This shows that HRC improves overall product quality and reduces waste.

Table 5 Simulation model results of the HRC WP1

	Machine/workplace							
Simulation model parameter	M1	M2	M3	WP1	M4	M5	M6	M7
Utilization (%)	36.8	82.9	94.9	95.9	90.9	99.1	58.3	41.6
Machine power consumption (kW)	127.0	1525.4	1746.2	13.2	1672.6	683.8	1072.7	143.5
Processing costs (EUR)	359.2	1380.5	1580.3	1525.5	1723.6	964.6	1105.4	406.1
Idle costs (EUR]	308.2	190.8	56.9	65.2	172.5	8.8	790.7	570.1
Number of finished products (pcs)	5515							
Scrap products (pcs)	344							

Fig. 5 presents that HRC WP1 significantly improves machine utilization, reducing idle time and improving overall productivity. The higher utilization in HRC indicates that CR help manage tasks, reducing worker strain and improving throughput. The average utilization of the manual assembly WP1 was 69.7 %, reflecting a high workload on human workers but suboptimal distribution of tasks across other machines. In the HRC system, the average utilization increased to 85.8 %, showing a more balanced distribution of work between humans and robots, leading to better resource efficiency.

Fig. 6 demonstrates that while the HRC system consumes more energy, this increase is accompanied by improved production efficiency. The trade-off between higher energy use and greater output efficiency is clear in the comparison, where total power consumption for the manual assembly WP1 was 5465.2 kW, with machines like M2 and M3 consuming a significant portion of energy. The HRC setup showed a higher total power consumption of 6984.2 kW, mainly due to the added power required for HRC WP1 (13.2 kW vs. 4.5 kW in the manual assembly WP1).

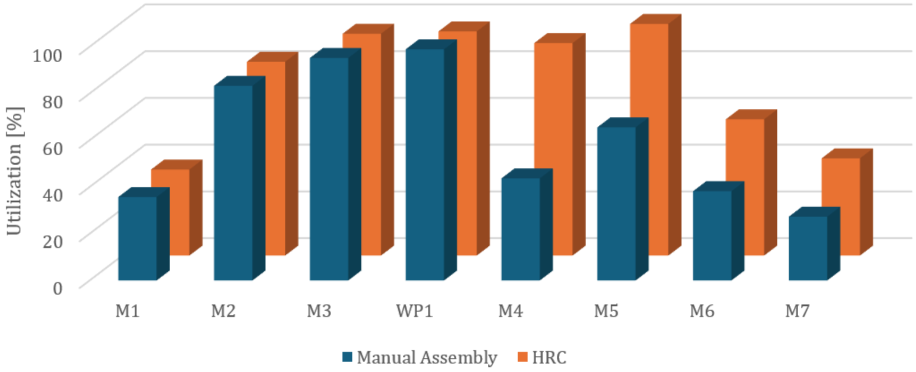


Fig. 5 Workplaces utilization results comparison

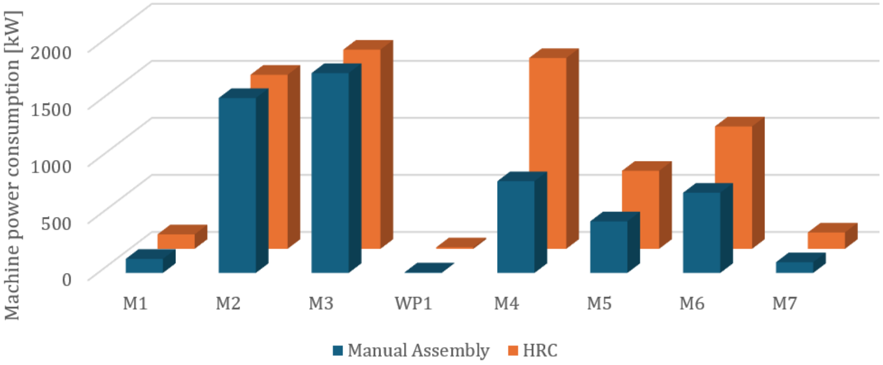


Fig. 6 Workplaces power consumption comparison

The total processing costs at the manual assembly WP1 amounted to 7211.8 EUR, largely driven by the intensive human labour required. Processing costs in the HRC system were 9045.1 EUR, reflecting the higher costs associated with integrating CR, but also the benefits of increased productivity. As shown in Fig. 7, the higher costs of HRC are offset by the increase in finished products, making it a more cost-effective option in the long term due to the reduction in errors and improved utilization.

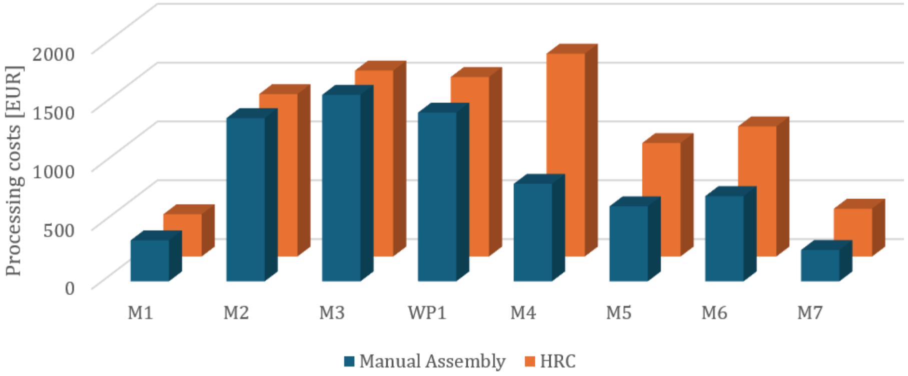


Fig. 7 Processing costs results comparison

In Fig. 8, idle costs for the manual assembly WP1 were high, totalling 3540.6 EUR, with machines such as M7 incurring significant idle time due to underutilization. The HRC WP1 dramatically reduced idle costs to 2163.2 EUR, as the CR helped minimize downtime by keeping machines and workers engaged in tasks.

As shown in Fig. 9, the integration of HRC not only increased total production but also improved product quality by reducing the scrap rate, which is essential for sustainable production systems.

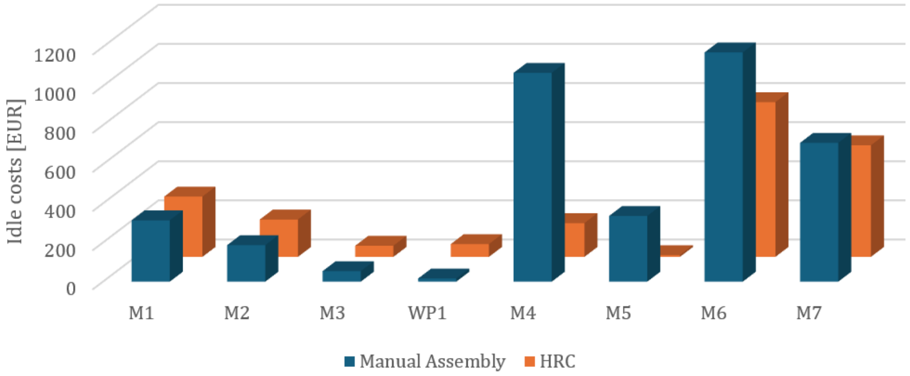


Fig. 8 Idle costs results comparison

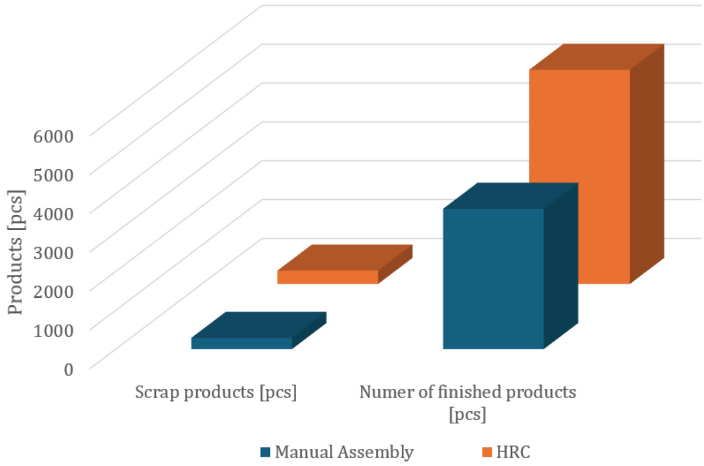


Fig. 9 Number of finished and scrap products comparison

5. Discussion

The results demonstrate the advantages of HRC workplaces in the context of Industry 5.0 manufacturing, particularly from the human-centred manufacturing perspective. By integrating HRC at the WP1, we observed improvements in both production efficiency and sustainability, aligned with proposed ESG criteria in Fig. 1. Regarding energy consumption per product, at the manual assembly WP1, the average energy consumption was 1.51 W per product, where at the HRC WP1 energy consumption decreased to 1.27 W per product, representing a 15.9 % electrical energy consumption reduction. This reduction in energy consumption is attributed to the optimized task distribution between worker and CR. The HRC help reduce idle times and ensure smoother production flows, thus lowering the energy footprint per product. In the context of ESG, this improvement supports environmental sustainability, as reduced energy use leads to lower carbon emissions and a more energy-efficient production. On the other hand, processing costs per product at the manual assembly WP1 were 2 EUR per product, where at the HRC WP1 processing costs dropped to 1.64 EUR per product, resulting in an 18 % processing cost reduction. The integration of CR in the HRC significantly lowers labour costs, as robots take over repetitive and high-strain physical tasks, enabling workers to focus on higher-value tasks. This reduction in processing costs underscores the economic benefits of HRC, making it a more cost-effective solution over the long term, particularly when considering reduced errors and improved output quality. More detailed costs evaluation was taking into concern with the idle costs per product parameter where idle cost for manual assembly WP1 were 0.98 EUR per product. At the HRC WP1 idle costs were reduced to 0.39 EUR per product, indicating a significant 60.2 % decrease. The reduction in idle costs demonstrates the enhanced efficiency of HRC, as CR can maintain consistent operations and reduce downtime between tasks. From a governance perspective, this improvement in resource utilization reflects better production capacity, which is critical in highly dynamic production environments. If summarizing total cost per product at the manual assembly WP1 were 2.98 EUR and at the HRC WP1 were reduced to 2.03 EUR, representing a 31.9 % total cost reduction. This significant reduction in total costs per product reinforces the economic advantages of HRC. Not only does HRC improve resource utilization, but it also reduces operational costs, leading to a more sustainable manufacturing process that aligns with ESG goals. Form the environmental view the production output and scrap rate were evaluated, where at the manual assembly WP1 3613 finished products with a scrap rate of 8 % were made. At the HRC WP1 output quantity increased to 5515 finished products with a reduced scrap rate of 4.5 %. HRC's higher production output and lower scrap rate reflect the improved product quality and efficiency of HRC. This improvement supports the social sustainability aspect of ESG, as it reduces waste, improves product reliability, and enhances the overall working environment. The HRC offers substantial benefits in terms of human-centred manufacturing, which is a core principle of Industry 5.0. By redistributing tasks between humans and CR, HRC ensures that workers are less exposed to physically demanding or monotonous tasks, which contributes to better worker well-being and reduces stress levels. This improvement in working conditions supports the social pillar of ESG, emphasizing safety, engagement, and health in the workplace. The increased production efficiency and reduced waste contribute to the environmental and governance aspects of ESG by minimizing resource use, enhancing productivity, and promoting more sustainable and responsible manufacturing practices.

6. Conclusion

The implementation of the HRC workstations in manufacturing has been shown that can lead to significant improvements in both economic and production processes performance, while simultaneously supporting sustainability goals as defined by ESG criterion. By reducing energy consumption, processing costs, idle times, and scrap rates, HRC systems offer a way to optimize production efficiency while enhancing the working environment. The integration of HRC is not only beneficial from an economic standpoint, but it also directly impacts worker well-being, a central theme in Industry 5.0. By redistributing strenuous and repetitive tasks to CR, workers experience lower physical and cognitive stress, leading to improved job satisfaction. This reinforces the social sustainability aspect of the ESG framework, ensuring safer and healthier workplaces. Presented results emphasize the potential for HRC to drive the future of manufacturing, enabling a harmonious balance between productivity, worker well-being, and environmental responsibility. As industries continue to move toward sustainable manufacturing, HRC systems present a solution for maintaining competitiveness while addressing the increasing demand for ethical and sustainable production practices.

The presented research has broad applicability across various industries. The findings from this research could be applied in the manufacturing processes optimization, where the distribution of labour and production capacities between manual and automated systems can enhance overall production system performance. Insights can support the integration of ESG criteria into operational decision-making, ensuring that manufacturing systems are not only economically viable but also socially and environmentally responsible.

In the future research we will focus on evaluation the physical and mental stress experienced by workers in HRC environments. Wearable technologies such as heart rate monitors or stress sensors will be employed to measure the impact of HRC on worker health. With those we will be able to provide additional insights into the human-centred design of workstations. While HRC systems improve operational performance, the next step is to optimize these systems for worker well-being. This could involve adjusting CR parameters to reduce cognitive load and physical strain on workers, potentially using adaptive algorithms that adjust CR speeds and tasks in real-time based on worker feedback. In addition, our future research work involves integrating worker knowledge management into HRC systems. By leveraging worker experience and expertise, manufacturing systems could be dynamically adapted to improve both efficiency and quality. For example, artificial intelligence driven knowledge management systems could capture worker inputs and suggestions, enhancing manufacturing system performance and further reducing errors or downtime. Incorporating these research directions would help evolve the Industry 5.0 paradigm, where human creativity and knowledge are enhanced by CR and artificial intelligence, leading to a more sustainable, efficient, and worker-friendly production environment.

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