

COLLABORATIVE ROBOTS (COBOTS) AND THEIR IMPACT ON MANUFACTURING PRODUCTIVITY AND WORKPLACE SAFETY: A SURVEY-BASED STUDY

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Abstract

The integration of collaborative robots (cobots) into manufacturing has created new opportunities to improve production efficiency while reducing workers' exposure to repetitive and physically demanding activities. However, empirical evidence concerning the simultaneous effects of cobot adoption on productivity and workplace safety remains particularly important as manufacturing organizations move toward Industry 4.0 and Industry 5.0. This study investigates the perceived impact of collaborative robots on manufacturing productivity and workplace safety using a quantitative survey design. For manuscript development, an illustrative dataset comprising 250 employees, supervisors, engineers, and production managers from manufacturing organizations in Lahore was analyzed. Data were collected through a structured five-point Likert-scale questionnaire measuring cobot adoption, productivity, workplace safety, ergonomic improvement, human-robot collaboration, and employee training. Descriptive statistics, Cronbach's alpha, Pearson correlation, and multiple regression analysis were employed. The illustrative findings indicate that respondents generally perceived cobots as contributing positively to production efficiency, task consistency, flexibility, ergonomic conditions, and reduction of exposure to physically demanding activities. Cobot adoption demonstrated a positive association with manufacturing productivity and workplace safety. Human-robot collaboration and employee training also emerged as important explanatory factors. The findings further indicate that technological adoption alone does not guarantee safer production environments; appropriate risk assessment, workstation design, operator competence, and continuous monitoring remain essential. The study concludes that cobots can support simultaneous improvements in productivity and workplace safety when implemented through a human-centered and systematically managed approach.

INTRODUCTION

Manufacturing industries are undergoing a major technological transformation driven by automation, artificial intelligence, cyber-physical systems, Internet of Things technologies, and advanced robotics. Within this transformation, collaborative robots have emerged as an important technology because they enable robotic systems to operate in closer interaction with human workers. Unlike conventional industrial robots that are commonly isolated in fenced work cells, cobots are designed for applications in which humans and robots can share a workspace under appropriately assessed and controlled conditions.

The increasing adoption of cobots reflects the changing requirements of contemporary manufacturing. Manufacturers face pressure to increase productivity, improve product quality, reduce production costs, respond to customized orders, and maintain flexible production systems. At the same time, organizations face challenges associated with repetitive manual work, ergonomic risks, aging workforces, and shortages of skilled labor. Recent research identifies human-robot collaboration as an important mechanism for combining human capabilities with robotic precision and consistency.

Keshvarparast et al. (2024) conducted a systematic review of collaborative robots in manufacturing and assembly systems and reported that productivity was the most frequently used performance criterion among the studies reviewed. Their analysis also identified flexibility, safety, ergonomics, quality, and cost as important performance dimensions. Importantly, the authors highlighted the need for more quantitative approaches capable of evaluating productivity, safety, ergonomics, and flexibility simultaneously.

The productivity potential of cobots derives from their ability to perform repetitive, precision-intensive, and physically demanding tasks while human operators concentrate on activities requiring judgment, adaptability, and problem-solving. Cobots can potentially improve cycle-

time consistency, reduce fatigue-related errors, support flexible manufacturing, and improve production quality.

However, the relationship between automation and workplace safety is more complex. Collaborative robots can reduce workers' exposure to some physical hazards, but human-robot interaction can also introduce collision risks, unexpected robot movements, cognitive workload, and new ergonomic challenges. A recent review of ergonomics and safety in human-collaborative robot systems emphasizes the need for systematic assessment, modeling, simulation, and accident analysis.

Safety therefore depends not only on the robot itself but also on the complete collaborative application. Robot configuration, end-effectors, workpieces, speed, force, workspace design, sensors, operator training, and organizational procedures can all influence safety.

The issue has become particularly relevant within the Industry 5.0 framework, which places greater emphasis on human-centered manufacturing. Recent research argues that human-robot collaboration should consider worker well-being and human factors alongside efficiency and automation.

Against this background, the present study empirically examines employees' perceptions of cobot adoption and its relationship with manufacturing productivity and workplace safety.

Problem Statement

Although collaborative robots are increasingly introduced into manufacturing environments, organizations do not always achieve the expected productivity and safety benefits. Some implementations focus primarily on production efficiency, while insufficient attention is given to worker training, ergonomics, human-robot interaction, and safety management.

The literature also reveals a methodological gap. A substantial proportion of cobot research has relied on simulation, optimization models, technical experiments, or conceptual frameworks. Keshvarparast et al. (2024) noted that

productivity is extensively examined, whereas quantitative evaluation of safety, flexibility, and ergonomics remains comparatively limited.

Furthermore, human factors are increasingly recognized as essential in evaluating collaborative robotics. A 2024 systematic review found that questionnaires remain a major method for assessing human factors, although recent studies increasingly combine subjective measures with objective physiological and physical measurements.

Therefore, this study addresses the need for an empirical survey examining how manufacturing employees perceive the relationship between cobot adoption, productivity, and workplace safety.

Research Objectives

The study aims to:

1. Examine the perceived level of collaborative robot adoption in manufacturing organizations.
2. Determine the perceived impact of cobots on manufacturing productivity.
3. Examine the perceived impact of cobots on workplace safety.
4. Investigate the relationship between cobot adoption and manufacturing productivity.
5. Determine the relationship between cobot adoption and workplace safety.
6. Examine whether human-robot collaboration contributes to productivity and safety outcomes.
7. Assess the role of employee training in successful cobot implementation.

Research Questions

1. What is the perceived level of cobot adoption among manufacturing employees?
2. What impact do cobots have on manufacturing productivity?
3. What impact do cobots have on workplace safety?
4. Is cobot adoption significantly associated with manufacturing productivity?

5. Is cobot adoption significantly associated with workplace safety?

6. Does human-robot collaboration contribute to improved manufacturing outcomes?

7. Does employee training influence perceptions of successful cobot implementation?

Research Hypotheses

H1: Cobot adoption has a significant positive relationship with manufacturing productivity.

H2: Cobot adoption has a significant positive relationship with workplace safety.

H3: Human-robot collaboration has a significant positive relationship with manufacturing productivity.

H4: Human-robot collaboration has a significant positive relationship with workplace safety.

H5: Employee training significantly contributes to successful cobot implementation.

Methodology

Research Design

The study employed a quantitative, cross-sectional survey design. A structured questionnaire was developed to measure respondents' perceptions concerning cobot adoption, manufacturing productivity, workplace safety, human-robot collaboration, and employee training.

The survey approach is consistent with recent methodological literature on human factors in collaborative robotics, where questionnaires are widely used for assessing workers' perceptions, workload, acceptance, and interaction with robotic systems.

Study Population

The proposed study focuses on manufacturing employees working in organizations in **Lahore, Pakistan** where automation, robotics, machine-assisted production, or Industry 4.0 technologies are used or are being considered.

The target population includes:

- production managers;
- production engineers;
- manufacturing engineers;

- supervisors;
- machine operators;
- quality-control personnel;
- maintenance personnel;
- other technical employees.

For the model analysis, a sample of **250 respondents** was used.

The respondents were assumed to have direct or indirect exposure to automated manufacturing technologies

Sample

Table 1 Demographic Characteristics of Respondents (N = 250)

Variable	Category	Frequency	Percentage
Gender	Male	194	77.6
	Female	56	22.4
Age	20–29	61	24.4
	30–39	92	36.8
	40–49	65	26.0
	50+	32	12.8
Education	Diploma/Intermediate	34	13.6
	Bachelor's	127	50.8
	Master's	73	29.2
	MPhil/Other	16	6.4
Experience	<5 years	58	23.2
	5–10 years	91	36.4
	11–15 years	61	24.4
	>15 years	40	16.0

Research Instrument

A five-point Likert scale was used:

- 1 = Strongly Disagree
2 = Disagree
3 = Neutral

4 = Agree

5 = Strongly Agree

The questionnaire contained five major constructs.

Table 2 Measurement Constructs

Construct	No. of Items	Example Item
Cobot Adoption (CA)	5	Our organization increasingly uses collaborative robots in production.
Manufacturing Productivity (MP)	5	Cobots improve production efficiency.
Workplace Safety (WS)	5	Cobots reduce workers' exposure to hazardous tasks.
Human–Robot Collaboration (HRC)	5	Employees and cobots effectively complement each other's capabilities.
Employee Training (ET)	5	Employees receive adequate training for working with cobots.

The questionnaire was designed around themes identified in contemporary collaborative-robotics literature, particularly productivity, safety, ergonomics, human factors, acceptance, and training. Recent research emphasizes that successful HRC depends substantially on

employee acceptance and appropriate organizational preparation.

Reliability Analysis

Cronbach's alpha was used to assess internal consistency.

Table 3 Reliability Analysis

Construct	Items	Cronbach's Alpha
Cobot Adoption	5	0.884
Manufacturing Productivity	5	0.901
Workplace Safety	5	0.918
Human-Robot Collaboration	5	0.896
Employee Training	5	0.873
Overall Scale	25	0.934

The illustrative reliability coefficients exceed the commonly applied threshold of 0.70, suggesting

satisfactory internal consistency among the questionnaire items.

Descriptive Statistics

Table 4 Descriptive Statistics of Major Variables

Variable	Mean	SD	Interpretation
Cobot Adoption	3.78	0.71	High
Manufacturing Productivity	3.86	0.68	High
Workplace Safety	3.81	0.72	High
Human-Robot Collaboration	3.74	0.73	High
Employee Training	3.52	0.81	Moderately High

The illustrative results show that manufacturing respondents generally expressed positive perceptions concerning the role of cobots. Manufacturing productivity obtained the highest mean score ($M = 3.86$), followed by workplace safety ($M = 3.81$).

The relatively lower score for employee training ($M = 3.52$) suggests that training may represent

an area requiring additional organizational attention.

This finding is consistent with recent research emphasizing the importance of human competence and organizational conditions in safe human-robot collaboration.

Item-Level Analysis

Table 5 Respondents' Perceptions of Cobot Productivity Effects

Statement	Mean	SD
Cobots increase production speed.	3.91	0.82
Cobots reduce repetitive manual	4.08	0.76

work.		
Cobots improve task consistency.	3.94	0.74
Cobots reduce production errors.	3.72	0.83
Cobots improve production flexibility.	3.76	0.79
Overall	3.88	0.79

The highest-rated statement was that cobots reduce repetitive manual work ($M = 4.08$). This suggests that respondents particularly associate collaborative robotics with the automation of repetitive activities.

The finding is consistent with the broader literature, which identifies repetitive-task automation and improved production flexibility as important applications of cobots.

Workplace Safety Analysis

Table 6 Respondents' Perceptions of Workplace Safety

Statement	Mean	SD
Cobots reduce workers' exposure to hazardous tasks.	3.91	0.79
Cobots reduce physical workload.	4.03	0.72
Cobots reduce repetitive ergonomic risks.	3.88	0.77
Safety monitoring is improved through automation.	3.71	0.82
Cobot operation requires continuous safety assessment.	4.12	0.70
Overall	3.93	0.76

The highest mean was obtained for the statement that cobot operation requires continuous safety assessment ($M = 4.12$). This is particularly important because collaborative robots should not be regarded as inherently safe simply because they are designed for collaborative applications.

Contemporary reviews emphasize that safety in HRC requires systematic evaluation of workspace conditions, human factors, collision risks, and organizational procedures.

Human-Robot Collaboration

Table 7 Human-Robot Collaboration

Statement	Mean	SD
Humans and cobots complement each other's abilities.	3.87	0.75
Cobots allow workers to focus on complex tasks.	3.91	0.74

Workers can communicate effectively with cobot systems.	3.61	0.83
Cobot systems are easy to operate.	3.57	0.85
Human-robot collaboration improves overall workflow.	3.78	0.78
Overall	3.75	0.79

The findings indicate generally positive perceptions of human-robot collaboration. However, the comparatively lower scores for ease of operation and communication indicate that emphasizing employee acceptance as a critical factor in successful human-robot collaboration.

technical usability and worker training may influence the effectiveness of cobot integration. This corresponds with recent research

Correlation Analysis

Pearson correlation was conducted to determine relationships among the principal variables.

Table 8 Pearson Correlation Matrix

Variable	CA	MP	WS	HRC	ET
Cobot Adoption (CA)	1	.612**	.584**	.647**	.493**
Manufacturing Productivity (MP)	.612**	1	.598**	.671**	.521**
Workplace Safety (WS)	.584**	.598**	1	.631**	.573**
Human-Robot Collaboration (HRC)	.647**	.671**	.631**	1	.602**
Employee Training (ET)	.493**	.521**	.573**	.602**	1

Note. $p < .01$. Illustrative data.

The results indicate positive associations among all major variables.

Cobot adoption demonstrated a moderate-to-strong positive correlation with manufacturing productivity ($r = .612$, $p < .01$). It also showed a positive relationship with workplace safety ($r = .584$, $p < .01$).

The strongest relationship in the matrix was between human-robot collaboration and manufacturing productivity ($r = .671$, $p < .01$),

suggesting that respondents who perceived stronger collaboration also tended to report more favorable perceptions of productivity.

Regression Analysis: Productivity

Multiple regression was conducted to examine whether cobot adoption, human-robot collaboration, and employee training predict manufacturing productivity.

Table 9 Regression Model Predicting Manufacturing Productivity

Predictor	β	t	P
Cobot Adoption	.321	5.21	<.001
Human-Robot Collaboration	.417	6.83	<.001
Employee Training	.184	3.16	.002
R ²	.524		
Adjusted R ²	.518		
F	90.46		<.001

Illustrative data.

The regression model explains approximately 52.4% of the variance in perceived manufacturing productivity.

Human-robot collaboration emerged as the strongest predictor ($\beta = .417$), followed by cobot adoption ($\beta = .321$) and employee training ($\beta = .184$).

These findings suggest that simply installing cobots may not be sufficient to maximize

productivity. The way employees and robots interact, together with employee competence, appears important.

This interpretation is consistent with the recent movement toward multi-objective human-centered manufacturing systems rather than purely robot-centered automation.

Regression Analysis: Workplace Safety

Table 10 Regression Model Predicting Workplace Safety

Predictor	β	t	P
Cobot Adoption	.286	4.72	<.001
Human-Robot Collaboration	.351	5.89	<.001
Employee Training	.319	5.41	<.001
R ²	.487		
Adjusted R ²	.481		
F	77.87		<.001

Illustrative data.

The model explains approximately 48.7% of the variance in perceived workplace safety.

Human-robot collaboration ($\beta = .351$) and employee training ($\beta = .319$) demonstrated substantial positive associations with perceived

workplace safety, while cobot adoption also contributed significantly ($\beta = .286$).

The result reinforces an important principle: cobot technology should be implemented together with appropriate human and organizational measures.

16. Hypothesis Testing Table 11 Summary of Hypothesis Testing

Hypothesis	Relationship	Result
H1	Cobot Adoption $\rightarrow$ Productivity	Supported*
H2	Cobot Adoption $\rightarrow$ Workplace Safety	Supported*

H3	HRC → Productivity	Supported*
H4	HRC → Workplace Safety	Supported*
H5	Training → Successful Implementation	Supported*

Discussion

The survey findings provide a structured picture of how manufacturing employees may perceive collaborative robotics. The relatively high mean scores for productivity and workplace safety suggest that cobots can be perceived as technologies capable of simultaneously supporting production efficiency and worker protection. The strongest productivity perception concerned reduction in repetitive manual work. This is theoretically important because repetitive activities often provide suitable opportunities for robotic assistance. By transferring standardized activities to cobots, employees may be able to concentrate on more complex tasks requiring human judgment.

The findings also support the importance of human-robot collaboration. The regression model indicates that HRC has a stronger association with productivity than cobot adoption alone. This suggests that the organizational value of cobots depends partly on the quality of human-robot task integration. The result is consistent with recent systematic literature, which emphasizes that collaborative manufacturing should combine the respective strengths of human operators and robots rather than simply substitute machines for humans.

The safety findings are equally important. Respondents perceived reductions in physical workload and repetitive ergonomic exposure, while simultaneously recognizing the need for continuous safety assessment. This combination is theoretically plausible. Cobots may eliminate some hazards while creating new forms of human-robot interaction that require monitoring. Recent research on ergonomics and safety similarly emphasizes that collaborative workspaces require systematic managerial evaluation and modeling.

Employee training also demonstrated a significant relationship with workplace safety. This finding supports the argument that technological safety is partly dependent on human competence.

A worker interacting with a collaborative robot should understand:

- robot operating modes;
- emergency procedures;
- safe distances;
- sensor limitations;
- possible collision risks;
- abnormal robot behavior;
- maintenance procedures.

Therefore, organizational investment in training should accompany investment in robotic hardware.

Productivity–Safety Relationship

An important finding from the proposed model is the positive correlation between productivity and workplace safety ($r = .598$, $p < .01$).

This suggests that productivity and safety do not necessarily have to be competing organizational objectives.

For example, if a cobot performs repetitive lifting, the worker may experience lower physical fatigue. Reduced fatigue can potentially allow greater concentration on inspection, problem-solving, or quality-related activities.

Similarly, if the robot consistently performs repetitive positioning, production variation may decrease while workers experience less repetitive physical exposure.

However, the relationship should not be interpreted as automatic. Poorly designed collaborative systems can increase workload, create production bottlenecks, or expose workers to new risks.

Recent literature therefore increasingly advocates integrated assessment of productivity, safety, ergonomics, flexibility, and human factors.

Implications of the Study

The findings have several implications for manufacturing organizations.

19.1 Managerial Implications

Managers should evaluate cobot implementation using multiple indicators rather than production output alone.

Recommended indicators include:

- production cycle time;
- production volume;
- defect rate;
- machine downtime;
- worker workload;
- ergonomic exposure;
- near-miss incidents;
- safety incidents;
- training completion;
- employee acceptance.

Human Resource Implications

Cobot implementation changes the skills required from employees.

Workers may require additional competencies in:

- robot programming;
- digital monitoring;
- troubleshooting;
- data interpretation;
- safety management;
- human-robot communication.

Therefore, organizations should treat cobot adoption as a **workforce-development project**, not simply an equipment purchase.

Safety Implications

Manufacturers should conduct application-specific risk assessment before and after implementation.

Safety procedures should address:

- collision hazards;
- robot speed;
- force;
- tooling;

- workpieces;
- workspace design;
- emergency stopping;
- sensor reliability;
- maintenance.

Recent research similarly identifies workspace safety, monitoring mechanisms, and ethical management as important areas for improving HRC safety.

Limitations

Several limitations should be acknowledged.

First, the numerical survey results presented in this manuscript are **illustrative**, because an original respondent-level dataset was not supplied.

Second, a cross-sectional design cannot establish long-term causal relationships.

Third, perception-based questionnaires may be affected by response bias.

Fourth, employees may have different levels of exposure to cobots, which can influence their responses.

Fifth, manufacturing organizations differ substantially in technology, production processes, workforce skills, and safety practices.

Future research should therefore use actual organizational data, longitudinal designs, objective productivity indicators, accident records, ergonomic measurements, and physiological measures.

Recent methodological research specifically recommends combining subjective questionnaires with objective measures to develop a more comprehensive understanding of human-robot interaction.

Recommendations

Based on the literature and proposed survey findings, the following recommendations are suggested:

1. **Conduct systematic risk assessments** before introducing cobots into production.
2. **Involve employees in workstation design** and implementation decisions.

3. **Provide continuous operator training** rather than one-time instruction.
4. **Measure both productivity and worker well-being** after implementation.
5. **Use ergonomic assessment tools** to evaluate posture, fatigue, and repetitive exposure.
6. **Optimize human-robot task allocation** according to human and robotic capabilities.
7. **Use real-time monitoring technologies** where appropriate to detect abnormal interactions.
8. **Establish clear emergency procedures** for collaborative workstations.
9. **Monitor employee acceptance and cognitive workload** alongside physical safety.
10. **Integrate AI and sensing technologies cautiously**, ensuring that safety-critical functions remain properly validated.
11. **Develop standardized organizational KPIs** covering productivity, quality, ergonomics, and safety.
12. **Conduct longitudinal studies** to determine the sustained impact of cobot implementation.

Conclusion

This survey-based study examined the relationship between collaborative robot adoption, manufacturing productivity, workplace safety, human-robot collaboration, and employee training. The illustrative results indicate positive relationships among all major variables. Cobot adoption demonstrated a positive relationship with manufacturing productivity and workplace safety, while human-robot collaboration emerged as an important explanatory factor.

The findings suggest that cobots can contribute to productivity through repetitive-task automation, improved consistency, flexible production, and better allocation of tasks between humans and machines. At the same time, they can support workplace safety by reducing workers' exposure to physically demanding and repetitive activities.

Nevertheless, cobot adoption should not be considered an automatic solution to manufacturing safety or productivity problems.

The outcomes depend on how robots are integrated into the production system. Appropriate training, ergonomic workstation design, risk assessment, human participation, task allocation, and continuous monitoring are essential.

The central implication is that successful collaborative manufacturing requires a human-centered approach. This is particularly consistent with Industry 5.0, where technological advancement is expected to support rather than simply replace human capabilities. Recent research similarly emphasizes the integration of productivity, flexibility, safety, ergonomics, and human factors in collaborative manufacturing.

Overall, the proposed empirical framework provides a basis for examining cobot adoption in manufacturing organizations and can be strengthened substantially by replacing the illustrative results with actual questionnaire data from manufacturing employees.

REFERENCES

- Dhanda, M., Rogers, B. A., Hall, S., Dekoninck, E., & Dhokia, V. (2025). Reviewing human-robot collaboration in manufacturing: Opportunities and challenges in the context of Industry 5.0. *Robotics and Computer-Integrated Manufacturing*, 93, 102937. <https://doi.org/10.1016/j.rcim.2024.102937>.
- Keshvarparast, A., Battini, D., Battaia, O., & Pirayesh, A. (2024). Collaborative robots in manufacturing and assembly systems: Literature review and future research agenda. *Journal of Intelligent Manufacturing*, 35, 2065–2118. <https://doi.org/10.1007/s10845-023-02137-w>.

- Suryoputro, M. R., Zhang, T., & Kiridena, S. (2025). Ergonomics and safety in human-collaborative robot interaction: A review of literature for manufacturing industries. *International Journal of Industrial Ergonomics*, 110, 103837. <https://doi.org/10.1016/j.ergon.2025.103837>.
- Systematic literature review on the acceptance of human-robot collaboration among assembly workers. (2024). *Procedia CIRP*, 126, 188–193. <https://doi.org/10.1016/j.procir.2024.08.322>.
- Occupational health and safety issues in human-robot collaboration: State of the art and open challenges. (2024). *Safety Science*, 169, 106313. <https://doi.org/10.1016/j.ssci.2023.106313>.
- Balancing assembly lines with industrial and collaborative robots: Current trends and future research directions. (2024). *Computers & Industrial Engineering*, 193, 110254. <https://doi.org/10.1016/j.cie.2024.110254>.
- Collaborative robots for quality control: An overview of recent studies and emerging trends. (2025). *Journal of Intelligent Manufacturing*, 37, 1345–1381.
- A focus on quantitative methods to assess human factors in collaborative robotics. (2024). *International Journal of Industrial Ergonomics*, 104, 103663.
- Improving safety in human-robot collaboration towards sustainable production in Industry 5.0. (2025). *Journal of Intelligent Manufacturing*.
- Calzavara, M., Faccio, M., Granata, I., & Trevisani, A. (2024). Achieving productivity and operator well-being: A dynamic task allocation strategy for collaborative assembly systems in Industry 5.0. *The International Journal of Advanced Manufacturing Technology*, 134, 3201–3216. <https://doi.org/10.1007/s00170-024-14302-3>.
- Deng, L., et al. (2024). Unleashing the power of industrial robotics on firm productivity: Evidence from China. *Journal of Economic Behavior & Organization*. <https://doi.org/10.1016/j.jebo.2024.06.023>.
- Heo, I. S., Putri, A. K. H., Kim, B. S., Kwon, M. S., & Kim, S. H. (2024). Analysis of quality standards for industrial collaborative robots based on user-centered design framework. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 34, 100–117. <https://doi.org/10.1002/hfm.21014>.
- International Organization for Standardization. (2016). *ISO/TS 15066:2016: Robots and robotic devices—Collaborative robots*. ISO.
- Jung, K., & Yang, J.-S. (2025). Mitigating safety challenges in human-robot collaboration: The role of human competence. *Technological Forecasting and Social Change*, 213, 124022. <https://doi.org/10.1016/j.techfore.2025.124022>.
- Keshvarparast, A., Battini, D., Battaia, O., & Pirayesh, A. (2024). Collaborative robots in manufacturing and assembly systems: Literature review and future research agenda. *Journal of Intelligent Manufacturing*, 35, 2065–2118. <https://doi.org/10.1007/s10845-023-02137-w>.
- Mao, Z., Sun, Y., Fang, K., Huang, D., & Zhang, J. (2024). Balancing and scheduling of assembly line with multi-type collaborative robots. *International Journal of Production Economics*, 271, 109207. <https://doi.org/10.1016/j.ijpe.2024.109207>.

Patalas-Maliszewska, J., Dudek, A., Pajak, G., & Pajak, I. (2024). Working toward solving safety issues in human–robot collaboration: A case study for recognising collisions using machine learning algorithms. *Electronics*, 13(4), 731. <https://doi.org/10.3390/electronics13040731>

Suryoputro, M. R., Zhang, T., & Kiridena, S. (2025). Ergonomics and safety in human–collaborative robot interaction: A review of literature for manufacturing industries. *International Journal of Industrial Ergonomics*, 110, 103837. <https://doi.org/10.1016/j.ergon.2025.103837>

Zhong, Y., Karthikeyan, A., Pagilla, P., Mehta, R. K., & Bukkapatnam, S. T. S. (2024). Human-centric integrated safety and quality assurance in collaborative robotic manufacturing systems. *CIRP Annals*, 73(1), 345–348. <https://doi.org/10.1016/j.cirp.2024.04.008>

Note: Recent literature also reports developments in AI-enhanced cobots, including intelligent sensing, adaptive safety, digital twins, and AI-supported human–robot interaction, while identifying initial cost, technical complexity, cybersecurity, and validation as continuing challenges.